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ASD-TR-61-716

A STUDY OF EXTINGUISHMENT AND CONTROL OF FIRES INVOLVING HYDRAZINE-TYPE FUELS WITH AIR AND NITROGEN TETROXIDE

TECHNICAL REPORT No. ASD-TR-61-716

MAY 1962

FLIGHT ACCESSORIES LABORATORY
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 6075, Task No. 607507

(Prepared under Contract No. AF 33(616)-6918
by Atlantic Research Corporation, Alexandria, Virginia.
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FOREWORD

This report was prepared by Atlantic Research Corporation, Alexandria, Virginia, on Air Force Contract AF 33(616)-6918 under Task No. 607507 of Project No. 6075, a Study of Extinguishment and Control of Fires Involving Hydrazine-Type Fuels with Air and Nitrogen Tetroxide. The work was administered under the direction of Flight Accessories Laboratory, Aeronautical Systems Division. Mr. Benito Botteri and Mr. Robert E. Cretcher were project engineers for the Laboratory.

The studies presented here, which began in December 1959 and were concluded in September 1961, represent the joint effort of the Nuclear Engineering and the Kinetics and Combustion Divisions of Atlantic Research Corporation. Dr. Michael Markels, Director of the Nuclear Engineering Division, was responsible for the experimental research effort and project administration; Dr. Raymond Friedman, Director of the Kinetics and Combustion Division, was responsible for the theoretical research effort; Mr. Wilburt Haggerty was the engineer in charge of the experimental work; Mr. Ralph Gill was the lead Technician; and Dr. Egon DeZubay contributed to some of the later phases of the work. The overall activity was carried out under Mr. Keith E. Rumbel, Vice President of Atlantic Research Corporation.

ABSTRACT

The proposed use of hydrazine-type fuels with nitrogen tetroxide in large missile systems has emphasized the need for information on materials and techniques for the extinguishment and control of fires arising from accidental spills of these propellants. In this investigation, burning rates, extinguishing agents, and extinguishment mechanisms were determined for open-pan fires of hydrazine, unsymetrical dimethylhydrazine (UDMH), JP-X, and a 50-50 mixture of hydrazine and UDMH oxidized by air and nitrogen tetroxide was studied in both open pans and in a 1/50 scale model of a Titan II silo.

Bicarbonate-based dry chemicals extinguished the pan fires most promptly, and with the least weight of agent. However, it was necessary to completely cover the burning surface and the fuel could be reignited. Water extinguished the fires by diluting the fuel surface. Course spray and alcohol-type foams were both effective forms of water application. After extinguishment by dilution, the fires could not be reignited. Water spray was not effective against JP-X fires because of the separation of a low-density, hydrocarbon-rich layer. Specific rates of application for selected agents under various fire conditions are given in the report.

The amine fuels (with the exception of JP-X, which was not tested), exploded hypergollically on contact with liquid nitrogen tetroxide in about half the tests. The likelihood of an explosion and the severity of the explosions seemed to depend on both the chemicals used and the geometry of the experiment. Explosions were attenuated, but not suppressed, by the addition of an inert component such as sand.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER

WILLIAM C. SAVAGE
Branch Chief
Environmental Branch
Flight Accessories Laboratory

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I. SUMMARY

The purpose of this investigation was to determine the materials and techniques necessary to extinguish and control fires involving hydrazine-type fuels with air and nitrogen tetroxide. The proposed use of hydrazine-type fuels in large missile systems has focused attention on the problem of providing fire protection to areas in which the fuels are stored, handled, or deployed in missiles. Because of the unusual properties of these fuels, conventional fire-fighting techniques and standards could be inadequate for fires arising from leaks or accidental spills.

In this investigation, screening tests using small fires (6.5-sq in) were conducted in the laboratory to evaluate extinguishing agents, which a theoretical analysis had indicated might be effective against hydrazine fires. The most promising agents were further evaluated in larger fires (up to 2304-sq in), in an outdoor facility to confirm and extend the small-scale results and to provide data for scaling factors. This approach permitted a large number of tests and provided better control and interpretation of variables than direct evaluation of large fires. More than 2,000 fires were burned during the investigation.

The fuels studied were: hydrazine, unsymetrical dimethylhydrazine (UDMH), a 50:50 mixture by weight of hydrazine and UDMH, and JP-X (40 per cent UDMH and 60 per cent JP-4 hydrocarbon fuel). Both air-oxidized and nitrogen tetroxide-oxidized fires were investigated. The results of the investigation are summarized below and in Table I.

A. HYDRAZINE

Hydrazine, because it can support a decomposition flame, burns at a rate approximately 10 times as fast as ordinary hydrocarbon fuels. Fires involving this fuel will be, therefore, very intense.

Water sprays effectively extinguished hydrazine fires by diluting the hydrazine to a concentration, which would not support combustion. Since this concentration is approximately 50 weight per cent, about one gallon of

Manuscript released by the authors December 1961 for publication as an ASD Technical Report.

TABLE I

Extinguishment of Fires Involving Hydrazine

Summary of Results of Pan Tests

Fuel	Extinguishing Agent[a]: Water Spray: Application[b] Rate (gpm/sq ft)	Water Spray: Amount[c,d] Required (gal water / gal fuel)	Water Spray: Time[e] Required (min/in fuel)	Alcohol Foam: Application[f] Rate (gpm/sq ft)	Alcohol Foam: Amount[f] Required (gal liq/sq ft)	Alcohol Foam: Ti Req (m
Hydrazine	0.8	1.0	0.73	0.4	0.1	0.
UDMH	0.8	2.5	1.95	0.4	0.25	0.
50:50 mixture of hydrazine - UDMH	0.8	2.0	1.56	0.4	0.15	0.
JP-X	0.8	Not satisfactory		0.4	0.16	0.

a. Amounts shown are actual requirements and do not include any safety factor.
b. Recommended rate of application per square foot of fire (use maximum rate available).
c. Minimum amount of agent required per gallon of fuel spilled.
d. Twice as much agent is required for fires oxidized by nitrogen tetroxide vapors.
e. Time required for extinguishment per inch of fuel depth when agent is applied at rate indicated
f. Based on gallons of liquid contained in the foam.
g. Time required for extinguishment when agent is applied at the indicated rate so as to cover the

Note:
1. Hydrazine at initial temperature of 140°F, UDMH, 50:50 mixture and JP-X at intial temperature o
2. Ten-second preburn time was used in all tests which were air oxidized unless otherwise noted.
3. Water spray should be coarse, 600 micron average drop size.
4. A 6 per cent alcohol foam was used with a 10:1 expansion ratio. Ordinary foams were ineffective.
5. The dry chemical was primarily sodium bicarbonate. Potassium bicarbonate was equally effective.

TABLE I

Involving Hydrazine-Type Fuels

esults of Pan Tests

uishing Agent[a]

cohol Foam		Dry Chemical			
Amount[f] Required (gal liq/sq ft)	Time[g] Required (min)	Application Rate (lb/sq ft-sec)	Amount Required (lb/sq ft)	Time[g] Required (min)	Remarks
0.1	0.25	0.02	0.04	0.033	Chlorobromomethane is ineffective, reacts with hydrazine
0.25	0.625	0.02	0.10	0.083	Trichlorotrifluoroethane is twice as effective per pound as water spray
0.15	0.375	0.02	0.10	0.083	Bromotrifluoromethane and carbon dioxide are both ineffective
0.16	0.40	0.02	0.10	0.083	

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ors.
d at rate indicated so as to cover entire burning surface.

so as to cover the entire burning surface.

intial temperature of 80°F.
otherwise noted.

ams were ineffective.
s equally effective.

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water was required per gallon of fuel. The nearly equal densities of water and hydrazine made it possible to form a water-rich layer on top of the hydrazine and to reduce the amount of water required to extinguish deep pools of hydrazine. Increasing the size of the fire slightly increased the amount of water required for extinguishment because the larger flames radiated more heat to the burning liquid and therefore vaporized more of the water droplets passing through the flame. The major scaling factor is the volume of hydrazine present. Fog was much less effective than water spray because the water droplets evaporated in the flame and reduced the amount of water available for dilution.

Because the alkaline hydrazine causes an alcohol-type foam to break down rapidly, the use of foam is, in effect, a gentle application of water. As the foam breaks down, a surface layer of water builds upon the surface of the fuel. This water-rich layer has little tendency to mix with the hydrazine because of little difference in their densities. The water thus not only dilutes the hydrazine, but protects the foam from the hydrazine vapors. Because of this extinguishing mechanism, the major scaling factor for foam application is the area of the fire. Approximately 0.1 gallon of water in the foam is required per square foot of fire, regardless of fuel depth. In the application of foam, mixing should be minimized. Because hydrazine and water are miscible, an alcohol-type foam should be used.

Dry chemical powders containing primarily sodium or potassium bicarbonate were also very effective against hydrazine fires, although the hydrazine could be reignited after extinguishment. When as little as 0.04 pound of powder per square foot of fire was applied rapidly, the fires extinguished regardless of fuel depth. The scale factor depends only on the surface area of the fire. As is the case with most dry-chemical applications, the unextinguished areas must be prevented from reigniting the extinguished areas. Complete coverage of the whole surface area at one time is desirable. An "ABC-type" dry chemical was not effective against hydrazine fires.

Chlorobromomethane reacted with hydrazine and failed to extinguish the fire. Because of the increased intensity of the fire and the dense fumes evolved, its use is considered hazardous.

B. UNSYMMETRICAL DIMETHYLHYDRAZINE

As UDMH does not burn as a monopropellant, its burning rate is comparable to that of the hydrocarbons. UDMH fires and hydrocarbon fires will have similar intensities.

UDMH fires were extinguished by water sprays when the fuel concentration was reduced to approximately 30 weight per cent; i.e., about 2.5 gallons of water per gallon of fuel were required for extinguishment. Because water is more dense than UDMH, there was no stratification of water on top of the UDMH. Although larger fires require slightly more water because of increased vaporization of the water droplets in the flame, the major scaling factor is the amount of UDMH present.

As was the case with hydrazine, an alcohol-type foam was a more efficient method of applying water to UDMH fires than spray, since, depending upon fire size, only one-half to one-third as much total water was required. Even though UDMH is less dense than water, deeper pools of UDMH required less foam than shallow pools per unit volume of fuel. Increasing the fire size did not increase the amount of foam required per gallon of fuel at constant depth. The quantity of foam required is very dependent upon both fuel depth and mixing conditions of foam and fuel. At least 0.25 gallon of contained water per square foot of fire is required.

Dry chemical powders composed of sodium bicarbonate were effective against UDMH fires, but more agent was required than for hydrazine fires. Rapid application of 0.10 pound of powder per square foot of fire was necessary for extinguishment. If the fire was not completely covered, the fire flashed over the entire surface when the flow of powder stopped. In every case, the UDMH could be reignited by a hot wire after extinguishment.

Trichlorotrifluoroethane* was an effective agent against UDMH fires when applied at a rate of 0.5 gallon per minute per square foot. The fires could be reignited after extinguishment, but they burned less intensely. The probable mechanisms of extinguishment were dilution, blanketing, and the combustion-retarding action of the halogens. The

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* Freon 113

rapid extinguishment and smaller amount of agent required make tichloro-trifluoroethane a more effective agent than water sprays or foam. However, on the basis of the weight of agent required for extinguishment, sodium bicarbonate was much more effective. Approximately 1.0 gallon of trichloro-trifluoroethane per gallon of UDMH is required for extinguishment.

C. 50:50 MIXTURE OF HYDRAZINE AND UNSYMMETRICAL DIMETHYLHYDRAZINE

The vapors above the 50:50 mixture of hydrazine and UDMH are primarily UDMH, since the UDMH is easily distilled from the mixture. Fires involving the mixture, therefore, closely resemble UDMH fires during the initial stages and hydrazine fires during the final stages. The over-all burning rate of the mixture is similar to that of pure UDMH.

Because the burning characteristics of the mixture closely resemble those of pure UDMH, the requirements for extinguishment are very similar. Approximately 2.0 gallons of water spray per gallon of mixture are required for extinguishment. This is 80 per cent of the requirement for pure UDMH. As was the case with the pure components, the major scaling factor is the volume of fuel present, although larger fires require slight more water propertionately than smaller fires. There was little or no effect of fuel depth on the scaling factor.

The mechanism of extinguishment of the 50:50 mixture fires by foam is analogous to that for the extinguishment of pure UDMH fires by foam. Extinguishment consists of dilution of the surface of the burning fuel by water released when the foam collapses. Although 6.5- and 49 sq in fires required the same amount of foam as fires involving pure UDMH, the 329-and 2304-sq in fires required less foam. Approximately 0.15 gallon of contained water per sq ft of fire is required for the extinguishment of large fires by foam. An ordinary mechanical foam, as opposed to the alcohol-type, was ineffective against fires involving the mixture and showed only a slight improvement over water spray.

As was the case with the pure components, sodium bicarbonate powder was very effective against fires of the 50:50 mixtures. When powder was applied at a rate of 0.0133 lb/sec per sq ft of fire, 2304-sq in fires were extinguished in less than nine seconds. The amount of powder required was 0.12 lb/sq ft, regardless of fire size or fuel depth.

Neither carbon dioxide applied as a gas at a rate of 0.17 lb/sec per sq ft nor bromotrifluoromethane*, applied as a gas at a rate of 0.04 lb/sec per sq ft, extinguished small fires of the 50:50 mixture. These agents should not be relied upon for extinguishment of such fires.

The effectiveness of water spray, alcohol-type foam, and sodium bicarbonate dry powder was confirmed in tests against 50:50 mixture fires in a 1:50-scale model Titan II silo. In general, the results were similar to, and predictable by, the results from the pan-type fires. However, when the water spray nozzle was placed one foot from the surface of the burning fuel, the fire was smothered and extinguished in only 2 or 3 seconds. When the nozzle was located 3 feet from the burning fuel, the fire was extinguished in 32 seconds which would be the predicted time according to the dilution mechanism. Nozzle location and distribution would therefore play an important role in extinguishment of fires in a silo configuration.

D. JP-X

The burning rate of JP-X, a blend of 60 weight per cent of JP-4 hydrocarbon fuel and 40 weight per cent UDMH, was slightly less than that of UDMH. It burns with the smokey flame characteristic of hydrocarbon fuels.

Water sprays were ineffective against JP-X fires because when water was added to JP-X two immiscible layers formed, one a UDMH-water layer and the other a hydrocarbon layer. Since the hydrocarbon layer floated on top of the UDMH-water layer, the fire behaved like an ordinary hydrocarbon fire. The fires continued to burn until the hydrocarbon was consumed.

A 6 per cent, alcohol-type foam was effective against JP-X fires. Slower application rates and deeper pools of fuel increased the

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* Freon 13B1

amount of foam required, but the major scaling factor was the size of the fire. Approximately 0.16 gallon of contained liquid per square foot was required.

As was the case with the other hydrazine-type fuels, sodium bicarbonate dry chemical was very effective against JP-X fires. Approximately 0.10 pound per square foot was required for extinguishment.

E. EFFECT OF NITROGEN TETROXIDE VAPOR

All of the hydrazine-type fuels ignited hypergolically when they contacted nitrogen tetroxide vapors. The lowest concentrations of water-diluted fuels which ignited hypergolically or burned in nitrogen tetroxide vapors are shown in Table II.

TABLE II

Hypergolic Ignition or Combustion of Hydrazine-Type Fuels with Nitrogen Tetroxide Vapors

Fuel	Fuel Temperature (°F)	Minimum Concentration in Water (weight per cent) Hypergolic Ignition	Combustion
Hydrazine	80	60	50
	140	55	45
	205	-	35
UDMH	80	65	30
50:50 mixture	80	55	45
	140	50	-

As can be seen, in the event of spills which contact nitrogen tetroxide vapors, dilution with almost equal amounts of water will be required to prevent ignition and larger amounts will be required to extinguish fires.

The experimental results showed that almost twice as much water was required to extinguish the fires oxidized by nitrogen tetroxide as was required to extinguish air-oxidized fires. The amounts of water required are 1.7, 3.8, and 2.7 gallons of water per gallon of fuel for hydrazine, UDMH, and the 50:50 mixture, respectively.

F. EFFECT OF NITROGEN TETROXIDE LIQUID

Contact of liquid nitrogen tetroxide with either hydrazine, UDMH, or a 50:50 mixture of hydrazine and UDMH resulted in explosions which precluded any attempt at fire extinguishment.

The initial experiment, in which 10 ml of hydrazine and 10 ml of liquid nitrogen tetroxide were dumped simultaneously, resulted in an explosion which severely damaged the laboratory hood. In a series of 101 experiments using only 3 ml of one of the fuels (hydrazine, UDMH, or the 50:50 mixture), 54 mixtures exploded. In general, the reports from the explosions of pure hydrazine were louder than those of the 50:50 mixture of hydrazine and UDMH. However, one explosion of 3 ml of the mixture was louder than any of the explosions involving 3 ml of hydrazine. Two of the 1/4-inch safety-glass windows of the hood were cracked. The explosions involving pure UDMH were less severe than those of either the mixture or pure hydrazine with nitrogen tetroxide.

Drying hydrazine to less than 0.1 per cent water did not prevent an explosion; however, when the water in the mixture was raised from 2 to 5 per cent, the explosions were more severe. Addition of 5 weight per cent of ethanol, isopropanol, or aniline to the mixture did not affect the frequency or severity of the explosions.

A series of tests involving larger quantities of the 50:50 mixture was conducted in the outdoor facility to determine the scaling factors that governed the intensity of the explosions. Spills involving 9 or 27 grams of fuel from a height of 8 inches resulted in explosions which produced side-on pressures of 0.06 to 0.20 psi at 10 feet. The standard side-on pressure curves for TNT, if extrapolated to these small quantities, indicate that this is equivalent to between 0.002 and 0.065 grams of TNT. When 90 or 270 grams of fuel were spilled from a height of 18 inches, overpressures ranging from 0.16 to 1.1 psi were recorded at 10 feet. This is equivalent to between 0.035 and 9 grams of TNT. In general, two distinct explosions occurred when 90 grams of fuel were spilled and three distinct explosions occurred when 270 grams of fuel were spilled.

The fact that the overpressures from the 9- and 27-gram spills were of the same magnitude and that the 90- and 270-gram spills were equivalent suggests that the spill height or geometry as well as the quantities of fuel involved is of major importance in controlling the intensity of the explosions. The contact area and force of impact would depend on these variables. Further work will be necessary to determine the variables affecting the explosions and the scaling factors.

The explosions were attenuated but not suppressed when the oxidizer or fuel was allowed to soak into sand before the other liquid was spilled. A 1:1 dilution of nitrogen tetroxide with water prevented an explosion or fire when the 50:50 mixture of hydrazine and UDMH was spilled into the oxidizer. A 1:2 dilution of nitrogen tetroxide with water failed to suppress the explosion under similar conditions. A 1:1 dilution of the fuel with water did not prevent an explosion when nitrogen tetroxide was spilled.

An explosion with an overpressure of 30 psi occurred when 115 ml of nitrogen tetroxide were dumped into 115 ml of the 50:50 mixture in the 1:50-scale model Titan II silo.

It is concluded that any of the hydrazine-type fuels may react explosively upon contact with liquid nitrogen tetroxide. Until the appropriate scaling factors and parameters affecting the intensity of the explosions are determined, such fires should be approached only with caution and adequate safety equipment.

II. INTRODUCTION

The proposed use of hydrazine-type fuels in large missiles has emphasized the need for fire protection in areas in which these fuels are stored or transferred. The purpose of this investigation was to determine the materials and techniques necessary to extinguish and control fires of hydrazine-type fuels in air and in nitrogen tetroxide.

Most existing fire extinguishment technology has resulted from studies of hydrocarbon- and cellulosic-type fuels in air. Although several qualitative recommendations were reported, no systematic evaluation of extinguishing agents or quantitative data on hydrazine-type fuel fires was found in the literature. Because of the reactivity, monopropellant properties, and high toxicity of the hydrazines, conventional fire-fighting techniques and standards were judged inadequate.

In this investigation, screening tests using small fires (6.5 sq in) were conducted in the laboratory to evaluate extinguishing agents which a theoretical analysis had indicated might be effective against hydrazine fires. The most promising agents were further evaluated in larger fires up to 2304 square inches. This approach permitted a large number of tests under control conditions. Estimates of extinguishment requirements for operational fires are made from scaling laws derived from the four sizes of experiments. The cost of full size experiments precluded their inclusion in an engineering research program of this kind. The statistical nature of fire extinguishment results makes it manditory to repeat each experiment about five times to assure reliable data, further restricting the maximum size of the experiments which can be performed in an engineering research program.

The test fires were conducted in open-pan burners designed to control mixing, fuel depth, and fire area. Additional tests were conducted in a 1:50 model Titan II silo made from stainless steel pipe.

Three primary fuels were evaluated initially: hydrazine, unsymmetrical dimethylhydrazine (UDMH), and JP-X (40 per cent UDMH, 60 per cent JP-4 hydrocarbon fuel). The program was extended to include a 50:50 mixture by weight of hydrazine and UDMH, a storable liquid fuel

used in the Titan II missile. Fires of liquid fuels were studied in air and in liquid or gaseous nitrogen tetroxide (the oxidizer in Titan II). The physical properties of these substances are summarized in Table III.

Water, powdered salts, foam and several liquid organic agents were used as extinguishing agents.

Two papers relating to this work were prepared for presentation before the Division of Fuel Chemistry, American Chemical Society meeting in Chicago, Illinois, September 3 to 8, 1961. The first, "Extinguishment Studies of Hydrazine and Unsymmetrical Dimethylhydrazine Fires," by W. E. Haggerty, H. Markels, Jr., and R. Friedman, draws freely from the results of this project. The second, "Survey of Chemical Inhibition in Flames", by R. Friedman, reviews the current knowledge of chemical inhibition of flames.

This report summarizes the work completed under Tasks I through IV between December 1, 1959, and September 18, 1961.

TABLE III

Physical Properties of Propellants Investigated

	Hydrazine	UDMH	50:50 Mixture	JP-X	Nitrogen Tetroxide
Formula	N_2H_4	$(CH_3)_2N_2H_2$	50 per cent N_2H_4 50 per cent UDMH	60 per cent JP-4 40 per cent UDMH	N_2O_4
Liquid density, (gm/cu cm)	1.008	0.786	0.904	0.78	1.45
Vapor density (air = 1.0)	1.1	2.1	1.4	-	3.2
Melting Point, (°F)	34	-71	-	-	-
Boiling Point, (°F)	236	146	158	155	70
Flash Point, (°F) (closed cup)	104	34	38	-	-
Fire Point, (°F)	126	5	38	-	-
Flammability Limits in air, (volume per cent)					
Lower	4.7	2.5	-	-	-
Upper	100	95	-	-	-
Toxicity, (MAC[a] ppm)	1	0.5	0.5	1	2.5

a. Maximum allowable concentration

III. BACKGROUND

A. LITERATURE SURVEY

A series of reports* was found which described the properties, storage and handling characteristics, and fire and explosion hazards of hydrazine and UDMH. Much of the scanty information available on fire-fighting was repeated from one report to the next. Pertinent facts from various reports are summarized below.

Hydrazine will absorb both carbon dioxide and water vapor on contact with air thus changing its properties. It is also oxidized by air quite readily. Its vapor is toxic (1 ppm allowable), and so are its combustion products. Hydrazine can burn with a decomposition flame which does not require oxygen. The hydrogen produced by this flame can then burn as a diffusion flame with air.

Water was widely recommended for fighting hydrazine fires. If hydrazine is progressively diluted with water and maintained at the boiling point of the mixture,[17] solutions containing more than about 52 weight per cent water will not sustain a flame and solutions containing more than about 60 weight per cent water will not flash when contacted with a flame. It has been stated[19] that dilution with at least 1.5 parts of water per part of hydrazine is better than application of water as fog. Carbon dioxide is mentioned[11] as a second choice, but is considered much less desirable than water.

UDMH is hygroscopic, absorbs carbon dioxide, is oxidized readily by air, and is toxic (0.5 ppm allowable). Toxic vapors may be produced on combustion.

At 73°F, a solution of 52.5 ± 2.5 parts by volume UDMH and 47.5 ± 2.5 parts water is just flammable. However, there is a heat-of-mixing effect, so a just-mixed, UDMH-water solution will give a different limit, namely 47 ± 1 parts by volume UDMH to 53 ± 1 parts water. At 176°F, the limiting mixture is 27.5 ± 2.5 parts UDMH to 72.5 ± 2.5 parts water.[9]

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* Section IX, Bibliography

Westvaco[27] recommended large volumes of water fog for combatting UDMH fires. They also extinguished UDMH fires by dilution with 2 or more parts of water and with carbon dioxide. Carbon tetrachloride and chemical foams are not recommended because UDMH apparently deactivates the foam-forming surfactant.

The Liquid Propellant Safety Manual[19] recommends large quantities of water for large fires. Sodium bicarbonate is recommended as more effective than either Halon 1301, carbon dioxide or water spray against small pool fires (5 pounds of fuel). Edwards Air Force Base recommends water first and carbon dioxide as a second choice.

JP-X is a mixture of 60 weight per cent JP-4 (a petroleum fraction) and 40 weight per cent UDMH. If water dilution is used to fight fires, an immiscible, higher density layer of water and UDMH separates from the hydrocarbon. The hydrocarbon layer sustains combustion and requires excess water for extinguishment. General statements to the effect that JP-X should be treated as intermediate in properties between hydrocarbons and UDMH were found.

The U. S. Bureau of Mines at Pittsburgh, Pennsylvania, was visited. Discussions were also held with representatives of the Naval Research Laboratory, the Army Engineer Research and Development Laboratory, the Army Chemical Center, the Olin-Mathieson Chemical Company, and the Naval Air Rocket Test Station, as well as the sponsor, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

The National Fire Protection Association (NFPA) has published recommended minimum rates and times of application for the more common extinguishing agents. In general, the recommendations are sufficient for ordinary fires and contain adequate safety factors. However, certain fire situations may require faster rates or longer times of application. The recommended NFPA rates, application times, and amounts of agents for lqiuid fires are listed in Table IV.

TABLE IV

NFPA Recommended Minimum Values for Fire Extinguishment[a]

Agent	Application Rate	Application Time	Amount (lb/sq ft)
Water sprays	0.2 to 0.75 gpm/sq ft	5 min	-
Alcohol foams	0.1 to 0.27 gpm/sq ft	20 to 55 min[b]	-
Sodium bicarbonate	0.065 to 0.1 lb/sq ft per sec	3 to 10 sec	0.6 to 1.0
Carbon dioxide	2.5 lb/sq ft per min	1 min	2.5

a. National Fire Codes (1960-1961) Vol. IV, Fixed Extinguishing Equipment, NFPA, Boston, Massachusetts. (1960).

b. The NFPA recommends that a 20 to 55 minute supply of foam concentrate be kept available. In addition to the normal safety factor, this includes a reserve supply for protection until more foam concentrate can be purchased after a fire.

The choice of agent or agents for combatting fires involving liquid fuels depends on the specific fuel and quantities involved. The geometry and accessibility of the fire, the combustibility of the surroundings, the required speed of extinguishment, reignition hazards, and other factors.

Water is undoubtedly the least expensive, most readily available agent. It is easily applied and effectively extinguishes Class A fires in combustible solids. It's cooling and dilution effects usually prevent reignition hazards connected with liquid fires. But it is relatively ineffective against hydrocarbon-type fuels and may react violently with some compounds.

Foams provide a blanketing-type action and are especially suited for fires involving liquids. Alkaline or water-miscible fuels tend to decompose foams and render them ineffective. A special "alcohol-type" foam has been developed for use against fires involving water-miscible liquids such as alcohols.

Dry chemical agents contain primarily sodium bicarbonate. The chief extinguishing mechanism is thought to be inhibition of the combustion reaction. Although sodium bicarbonate is most effective against liquid fuel fires, recently developed ABC dry chemical powders form a molten slag on hot surfaces and are suitable for use on Class A or metal fires. The chief disadvantage of dry chemical powders is that, once extinguished, the fire can reignite.

Carbon dioxide acts by smothering and cooling liquid fuel fires. Because of inadequate confinement, it is difficult to apply to large outdoor fires in quantities sufficient to smother the fire.

Halogenated vaporizable liquid agents act by inhibition of combustion reactions. Because of their high cost their use is usually limited to small, confined, very inaccessible fires. Their reaction or decomposition in a fire results in the release of undesirable halogen acid vapors.

B. SCALING FACTORS FOR MODEL FIRES

Application of the results of controlled laboratory fires to fire extinguishment practice in the field depends primarily on the accuracy with which results can be extrapolated. Scaling problems in general have not been extensively studied, especially those involving advanced rocket propellants.

Since this program includes four sizes of fires, some data can be extrapolated. However, these are limited by the largest experimental fire, 16 square feet, which is still very small compared to those likely encountered in the field.

Important variables that complicate the problem of scaling are (1) burning rate, (2) extinguishment mechanism, (3) fire intensity, (4) fire geometry, and (5) the technique for applying the extinguishing agent.

The scaling of burning rates of liquids follows a relatively simple theoretical correlation. For an open pan fire, the linear rate of liquid regression, r, is believed independent of size for sufficiently large fires, in which cases radiation becomes the dominant mode of heat transfer. The emissivity of the flame gases then does not depend on flame size and approaches unity. Above the critical size the heat flux from flame to unit area of liquid should be constant; and hence r should reach a constant value, r_∞. Limited data, particularly those of Blinov and Khudiakov (USSR)[7] and the U. S. Bureau of Mines,[8] show that the asymptotic limit is approached for fires a few feet in diameter. The magnitude of this asymptotic rate r_∞ should depend mainly on flame temperature and heat of vaporization of the liquid.

Hottel[12] proposed a mathematical relation of the form

$$r = r_\infty (1 - e^{-Kd})$$

to describe the decrease of r with flame diameter, d, below the critical size. The constant K may be interpreted as an optical extinction coefficient for the flame gases.

The above relationship appears as a solid line in Figure 1. Also shown are the Bureau of Mines experimental points of the burning rate of hexane.[8] The solid line corresponds to a r_∞ of 0.75 cm/min and an extinction coefficient of 0.0190 cm^{-1}. The remarkable agreement between the experimental data and the theoretical curve confirms the validity of the theoretical analysis in this case. The experimental burning rate deviates from the theoretical curve at the smallest-diameter fire, probably because convective and conductive heat transfer around the rim of the pan become significant relative to radiation for pans smaller than a foot in diameter. Since the ratio of the perimeter to the area of a circular pan is inversely proportional to the diameter, the effect rapidly increases as diameter decreases. In practice, r increases with a decrease in diameter as shown by the dashed line. Since this behavior sharply depends on the detailed geometry and materials of construction of the test rig, the dashed line is strictly an estimate. The smallest test fire used in this investigation may be in the range where edge effects are important; however, the other three sizes shown should define the type of curve represented by the Hottel correlation, and extrapolation to larger sized fires should be feasible.

Even though the influence of burning rate on scaling factors is relatively simple, the extinguishment mechanism further complicates scale-up. Some of the mechanisms by which flames are extinguished are as follows:

(1) Blanketing: prevents air from reaching the fire or dilutes the vapors below the combustible limit.

(2) Cooling: cools either the vapors or the burning fuel below the ignition temperature.

(3) Mechanical: blows the flames away from the fuel.

(4) Radiation shielding: prevents heat transfer to the fuel from the flame.

(5) Chemical action: inhibits combustion reactions.

(6) Fuel dilution: reduces the fuel vapor pressure below the lower limit of flammability.

(7) Fuel complexing: decreases the chemical activity or vapor pressure of the fuel.

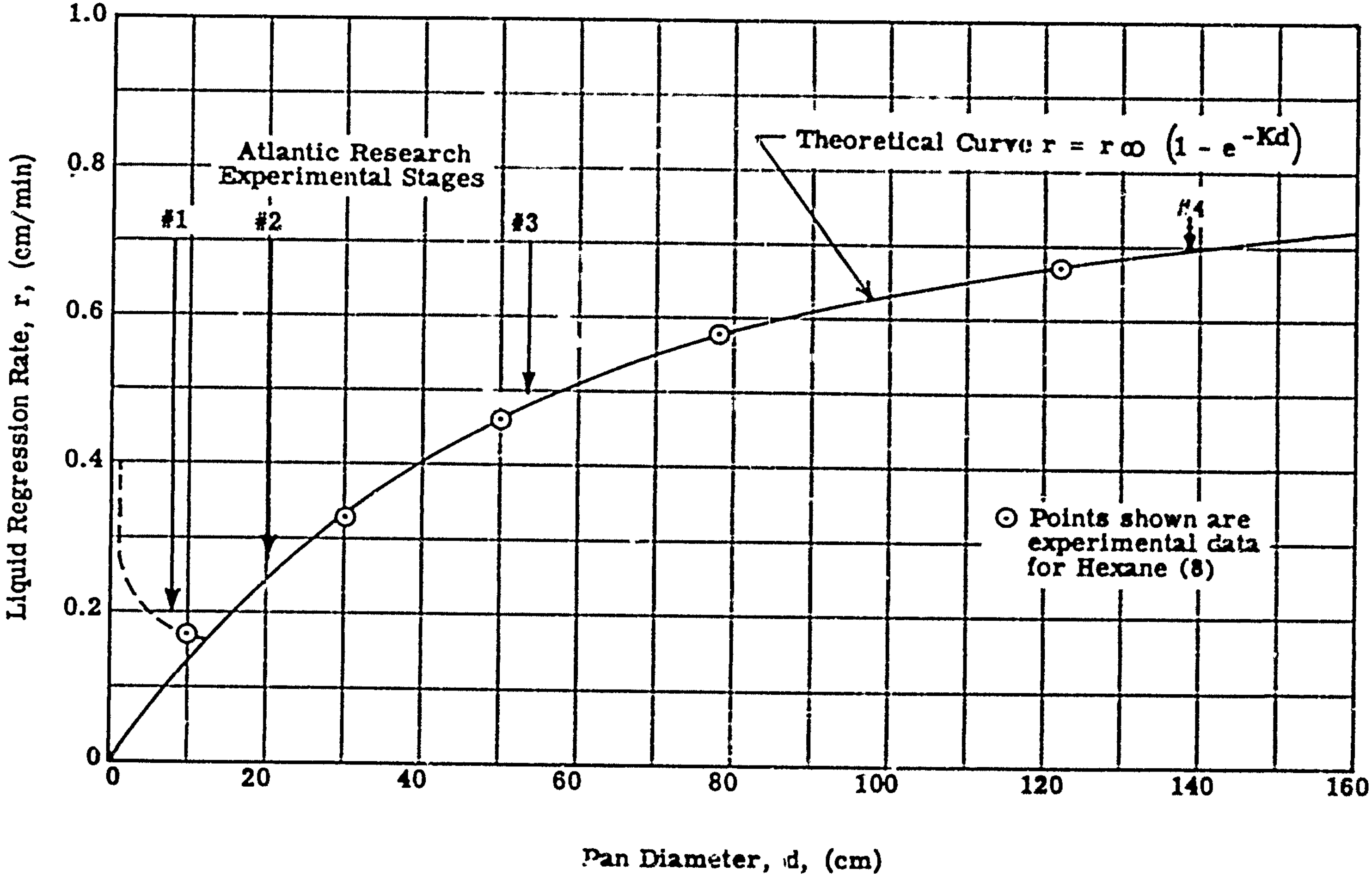

Figure 1. THE EFFECT OF PAN DIAMETER ON LIQUID REGRESSION RATE

Extinguishment by a water spray probably combines several mechanisms: (1) blanketing by steam formed in the hot vapors, (2) cooling by evaporation, (3) radiation shielding by water droplets, and (4) fuel dilution.

Even if only one mechanism is involved, scaling is often complex. For example, when the agent simply dilutes the fuel such as water applied to hydrazine, it might be assumed that the quantity of agent required depends on the quantity of fuel present and not on the diameter of the fire, viz., the same quantity of water extinguishes a 1-inch deep pool of 1-foot diameter and a 0.25-inch deep pool of 2-foot diameter. However, this assumption neglects the fact that a portion of the water evaporates in the fire before reaching the liquid. This portion depends on the geometry of the fire, the rate of application of the water, the surface area of the water, and the direction from which the water is added. This assumption also neglects any concentration gradients set-up in the liquid because of incomplete mixing. Because of the interactions of these variables, a theoretical approach is less meaningful and scaling experiments are necessary to determine the mechanisms governing the effectiveness of each agent on each type of fire.

The scaling factors for other complicating variables such as intensity, geometry, and application technique of the extinguisher, can be estimated roughly for specific cases of large fires.

One of the few scaling experiments reported in the literature was conducted by the National Bureau of Standards.[12] The necessary rate of powder application for extinguishment of heptane was directly proportional to dish area for diameters from 1.125 to 23 inches. Other data showed that this proportionality holds up to at least 100 inches of fire diameter. This indicates that the mechanism by which dry powder extinguishes hydrocarbon fires does not change with the size of the fire, and that scaling involves only the area of the fire.

IV. EXPERIMENTAL APPARATUS

A. BURNERS

1. Fire Extinguishment Tests

Burners were constructed for remote operations on controlled-area fires using square burner pans. Fires in four sizes of stainless steel pans were investigated: 6.5-, 49-, 324-, and 2304-sq in.

The apparatus in Figures 2 and 3 illustrate typical setups using the 6.5-sq in burners. The bottoms of the 6.5- and 49-sq in pans sloped towards the centers to insure rapid contact of fuel and oxidizer. A 3/4-inch freeboard at the sides reduced splashing and fuel spillage. A flat, stainless steel tray supported the burner pans and caught spilled propellant and excess extinguishing agent. Also, this tray minimized updrafts to the fires and cooling of the burner sides.

The 324- and 2304-sq in pans had flat bottoms with 2- and 3-inch freeboards, respectively. No trays were used. All pans were heated to maintain the liquid fuel about the fire point, or cooled to constant temperature below the boiling point of nitrogen tetroxide by circulating liquid through coils brazed to the undersides.

Stainless steel cylindrical reservoirs, pivoted at the sides of the burner, were used to dump either fuel or oxidizer into the burner pans. A hot wire ignited non-hypergolic mixtures. Fuel temperature before and during burning was measured with a thermocouple.

2. Hypergolic Liquid Spills

The equipment, shown in Figure 4, consisted of a spring loaded stainless steel reservoir which was inverted rapidly when a solenoid was activated, dumping either fuel or oxidizer into a stainless steel pan containing the other component. Two reservoirs were used. The first was used to dump 3-30 ml of liquid into a 3-inch diameter pan from a height of 8 inches. The other was used to dump 100-300 ml of liquid into an 8-inch diameter pan from a height of 18 inches.

The overpressures from the hypergolic reactions were measured by a pencil-type, zirconate piezoelectric transducer, sensitive to side-on pressures and displayed on an oscilloscope. A time-of-arrival blast gage located six inches in front of the sensing element of the transducer

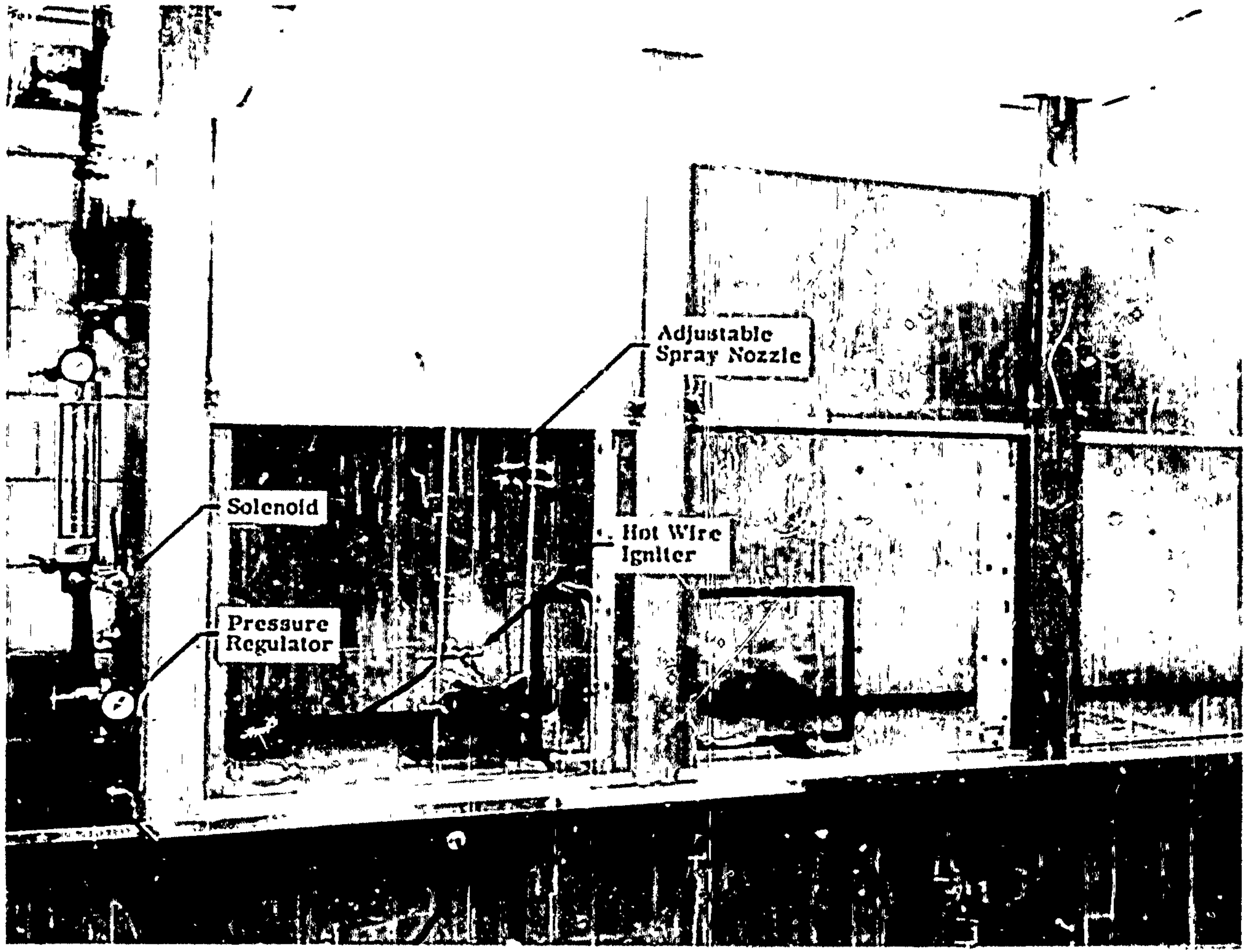

Figure 2. FIRES LABORATORY SHOWING BURNER TEST APPARATUS

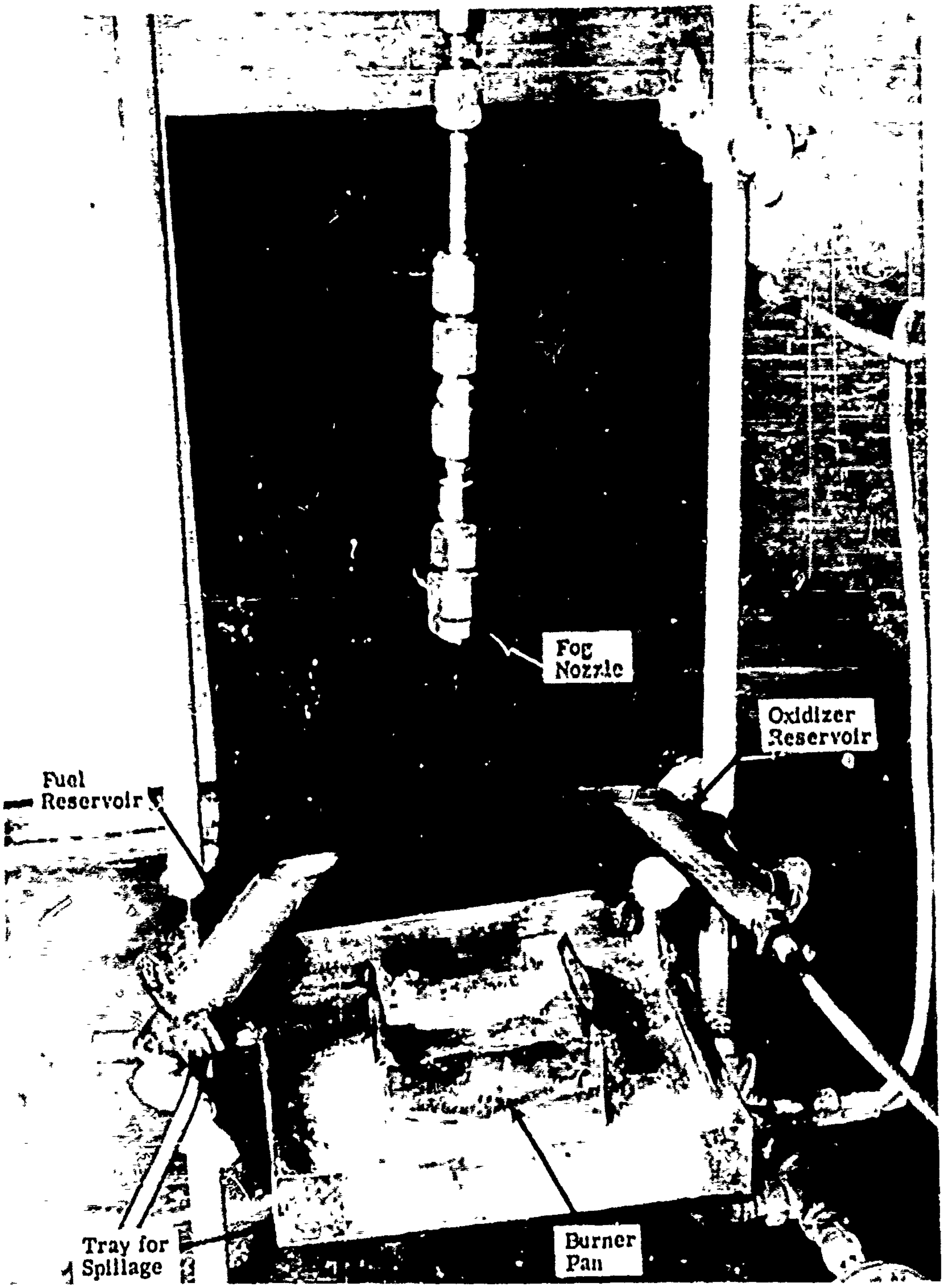

Figure 3. BURNER APPARATUS WITH SPRAY NOZZLE

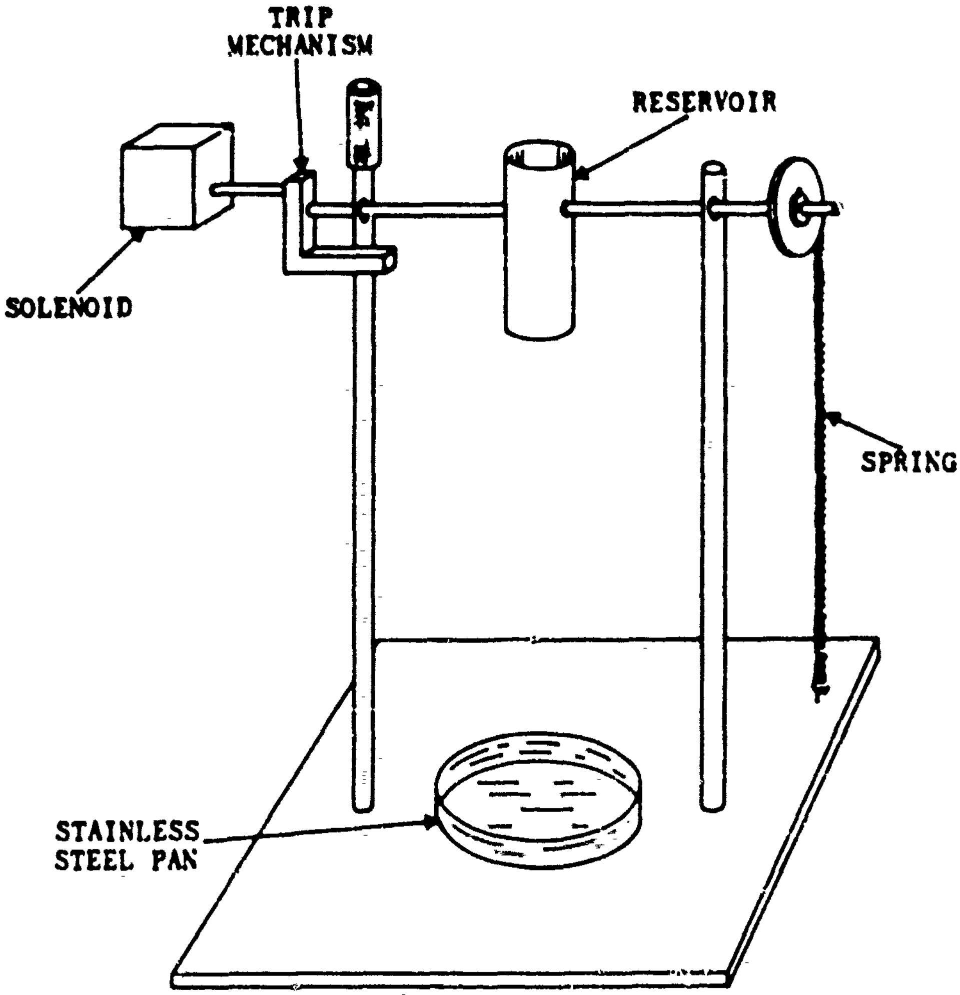

Figure 4. HYPERGOLIC SPILL APPARATUS

triggered the oscilloscope beam, which scanned the 4-inch face of the scope at a rate of 400 cps for each pulse. The oscilloscope trace was recorded on a 35 mm film strip moving at 40 in/sec. This arrangement permitted recording of multiple-blast waves and calculations of time intervals between waves.

3. Hypergolic Nitrogen Tetroxide Vapor

Fires of fuels oxidized in atmospheres of nitrogen tetroxide vapors were conducted by directing oxidizer vapors from a storage cylinder, through a jet, and over the surface of the fuel contained in a burner pan.

4. Model Silo

The model Titan silo was constructed from three feet of 12-in I.D., schedule 40, stainless steel pipe, a 150-lb welding neck flange, and a standard welding cap. This resulted in a silo of 12.00-in I.D., 46.5-in long with a volume of 2.9-cu ft. The silo was scaled therefore with a 1:50 diameter ratio and a 1:120,000 volume ratio to the prototype Titan II silo. All but 12-in of the silo was embedded below ground level. It is shown in Figure 5.

A simulated Titan missile, 2.5-ft of 2-in O.D., stainless steel tubing, was filled with water and placed 12-in above the bottom of the silo. Thermocouples were mounted on the inside and outside of the missile. The silo pressure at the level of the bottom of the missile was recorded with a pressure transducer.

B. FACILITIES

1. Laboratory

The 6.5-sq in fires were conducted in a 140-cu ft hood that was designed to remove toxic vapors and to withstand an overpressure of greater than one psi. This overpressure results from the confined oxidation of 10 ml of UDMH with nitrogen tetroxide and no cooling. A stainless steel pan protecting the bottom of the hood was easily flushed with water when fuel or oxidizer spilled. Four spray nozzles in the ceiling served as an emergency deluge system. Four windows of 1/4-inch safety plate glass enclosed the front of the hood and provided easy access.

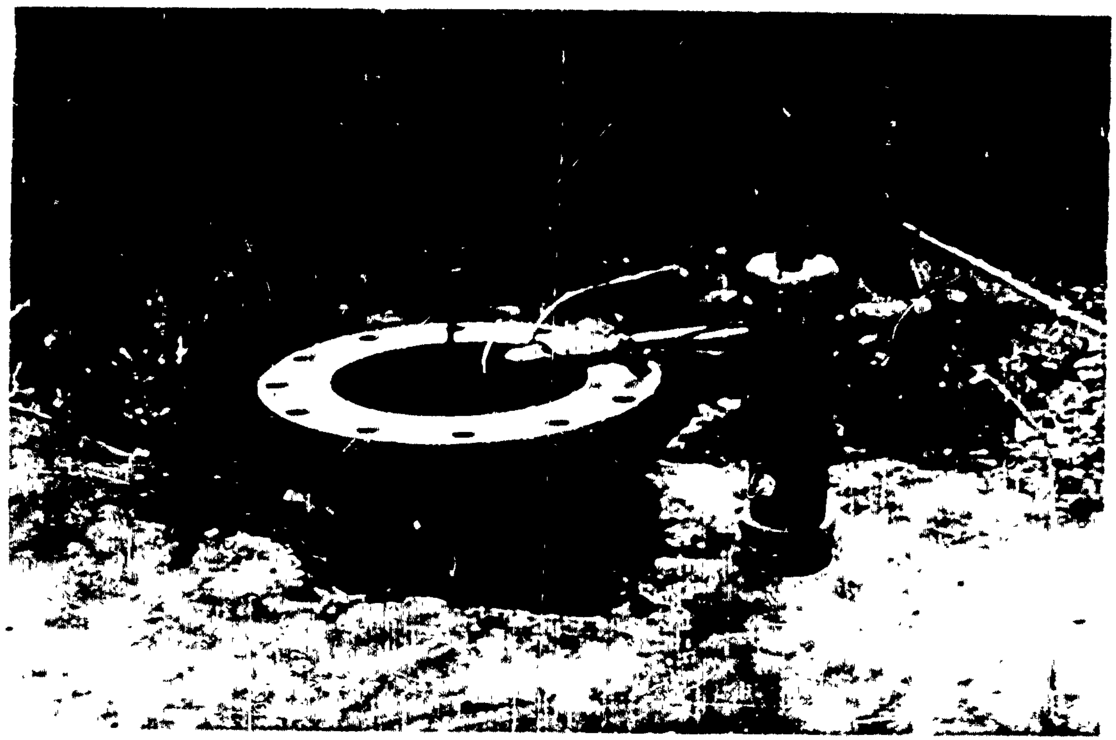

Figure 5. SCALED TITAN II MODEL SILO SHOWN WITH DRY CHEMICAL APPLICATOR

2. Outdoor

The 49-, 324-sq in burners were used in specially constructed outdoor facilities at the Pine Ridge Experiment Station, Gainesville, Virginia. The burning facility consisted of a 10-foot-square concrete pad surrounded by an 8-foot-high windbreak. As a safety precaution the pad was on an earth mound 6 feet above the level of operating personnel. Operations were monitored remotely from a control bay. The facility is shown in Figures 6 and 7. Additional windbreaks were constructed after the photographs were taken.

C. APPLICATORS

The literature was searched to determine the most promising fire-fighting techniques and to provide a basis for the design of the extinguishing agent applicators. Many reports stressed the difficulties in obtaining reproducible results when testing various extinguishing agents. The application rates and techniques must be closely controlled and were considered in the selection and design of applicators for the various agents. Manufacturers of fire extinguishing agents were consulted for the latest equipment developments. Foam, powder, and vaporizing liquid agents were included in this phase of the program.

1. Spray Nozzles

Spray nozzles capable of producing coarse sprays, fine sprays, fog, and pneumatic sprays were calibrated to define flow rate and spray distribution as a function of water and/or air pressure.

The spray nozzle apparatus consisted of:

(1) Stainless steel fulljet nozzles*. Although the weight-averaged drop size was not measured, calculations based on data from similar nozzles give a value of 160 microns for the spray used on the 6.5-sq. in fire, 243 microns for the spray used on the 49-sq in fire, 290 microns for the spray used on the 324-sp in fire, and 600 microns for the spray used on the 2304-sq in fire.

(2) A pressure regulator which was used to control the water pressure at the nozzle.

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*Spraying Systems Company

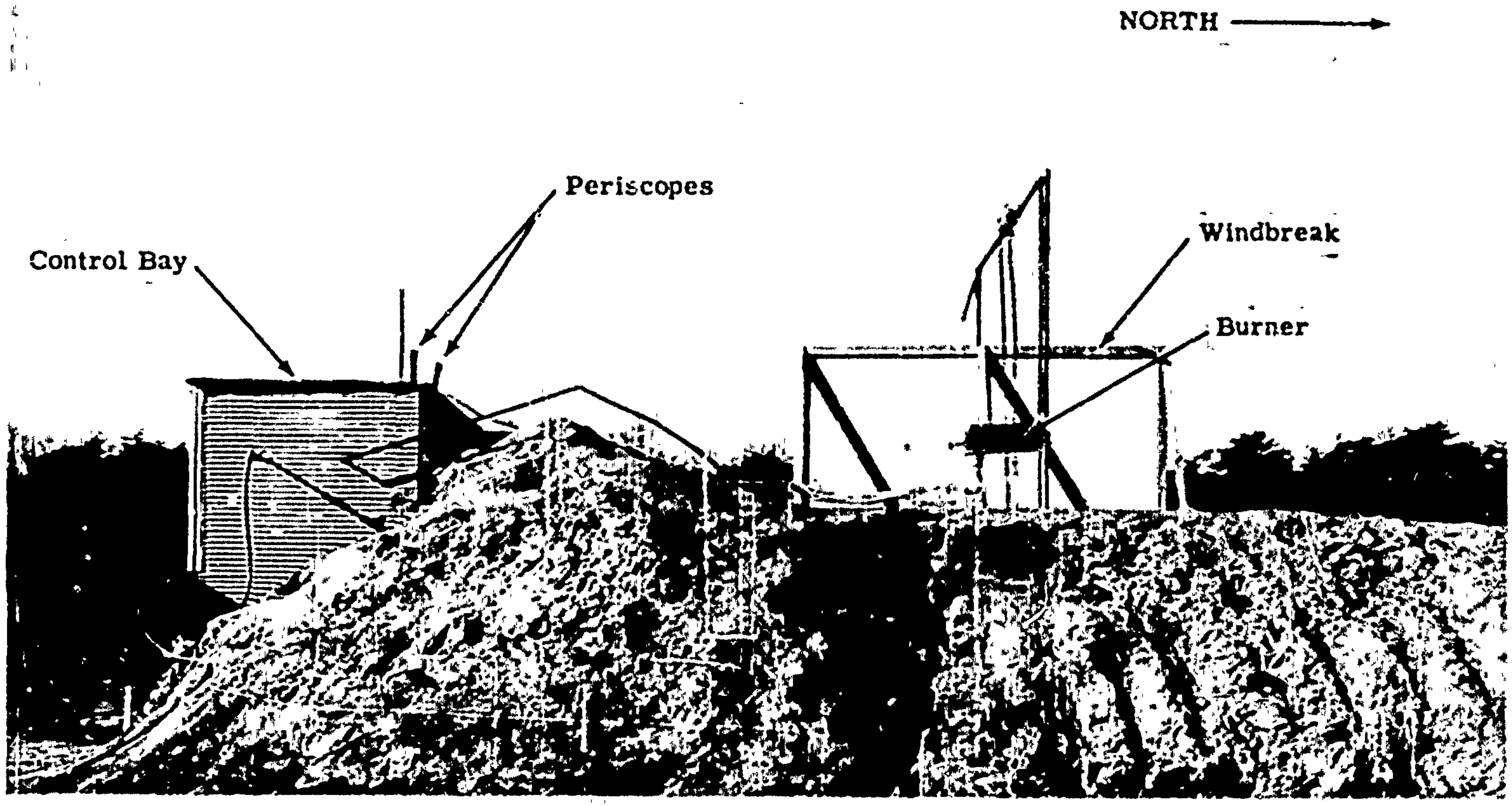

Figure 6. SIDE VIEW OF OUTDOOR FIRE EXTINGUISHMENT FACILITIES

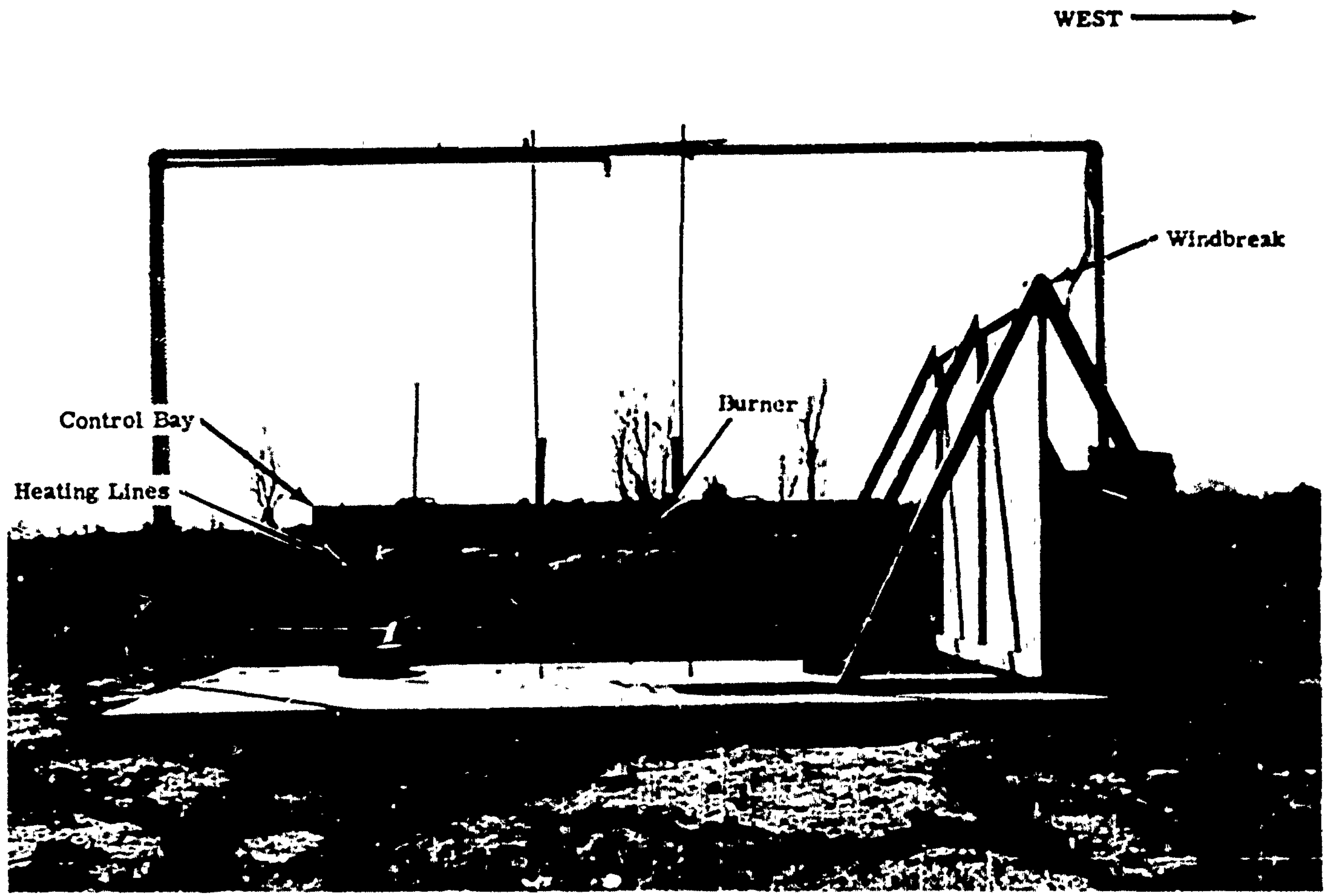

Figure 7. REAR VIEW OF OUTDOOR FIRE EXTINGUISHMENT FACILITIES

(3) A solenoid valve to start and stop application of the spray.

(4) A thermocouple to measure the temperature of the water entering the nozzle.

At a nozzle height of 18-in above the burning surface, the spray pattern was uniform over an 8-in diameter circle, which amply covered the 6.5-sq in pan. The surface of the burning liquid was visibly roughened by the spray droplets. Comparable coverage were obtained for the larger fires.

2. Foam Generator

A foam generator similar to one developed at the Midwest Research Institute[28] was used. However, because the alcohol-type foam concentrate coagulates if diluted more than a few minutes before it is expanded by forced air, the generator was modified. It is shown in Figure 8, and consisted of the following:

(1) Separate meters for foam concentrate, water, and air to allow for instantaneous mixing at the time of foam generation.

(2) A 2-ft-long section of 3/4-in copper tube packed with 5-mm glass beads to provide even air dispersion and small bubbles.

The apparatus can produce foams of good, reproducible quality at foam rates as low as 200 cu cm/min. By changing rotameters, rates to 34 liters/min can be applied. Depending upon the foam concentrations, foams with expansion ratios* of 10 to 15 and quarter times** of 4 to 15 minutes have been produced. These are equal to or slightly above the optimum foams recommended by the National Fire Protection Association and within the range of practical generating equipment. The control of foam rates and quality was good.

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* Ratio of foam volume to liquid volume.

** Time for 25 per cent of liquid to settle out.

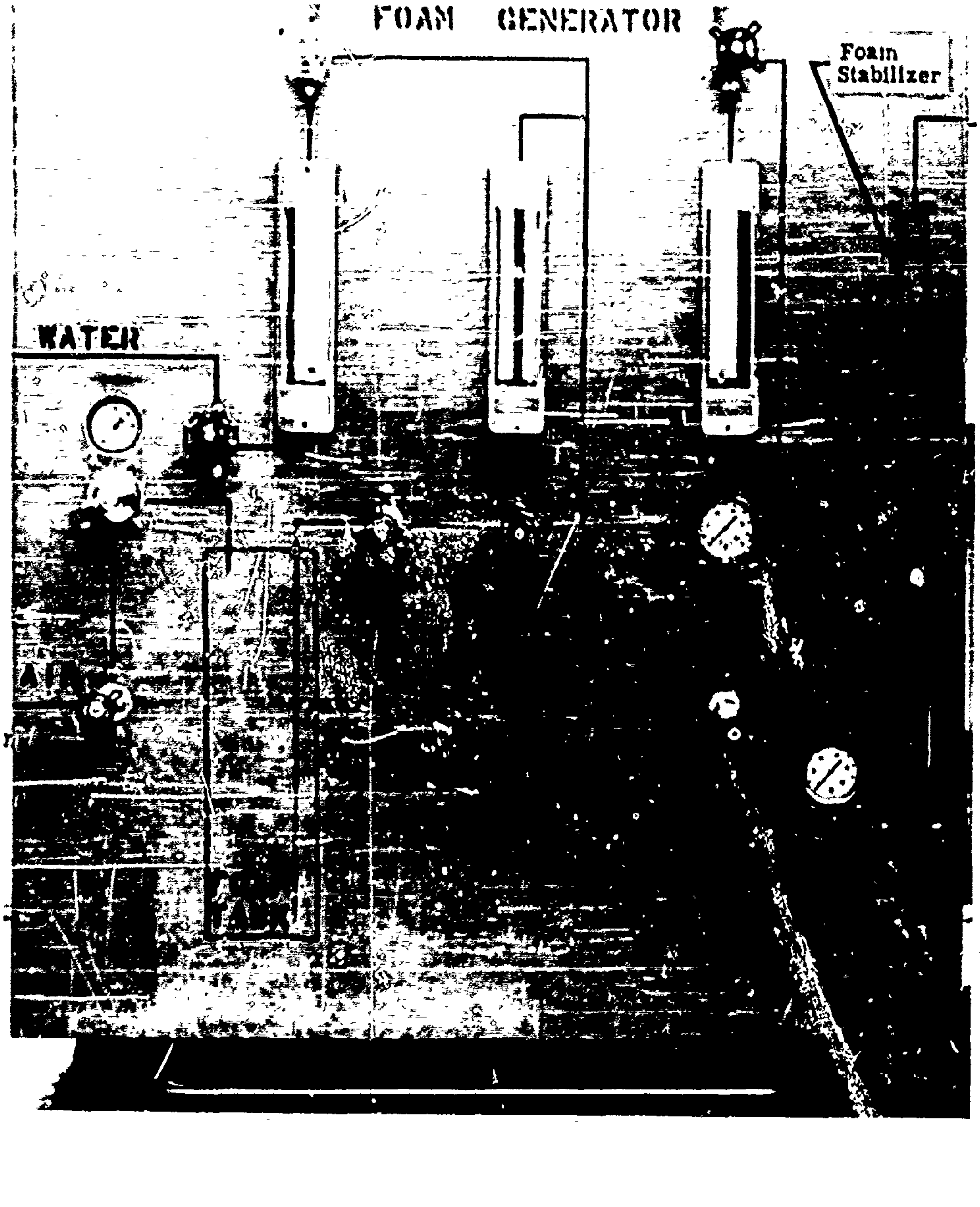

Figure 8. FOAM GENERATOR

3. Dry Chemical Applicator

An apparatus similar to that developed at the National Bureau of Standards by McCamy, Shoub, and Lee[22] applied dry powders to the fuel fires (See Figure 9). The applicator was constructed as shown in Figure 10. The addition of a rotameter to the original apparatus improved control and reproducibility.

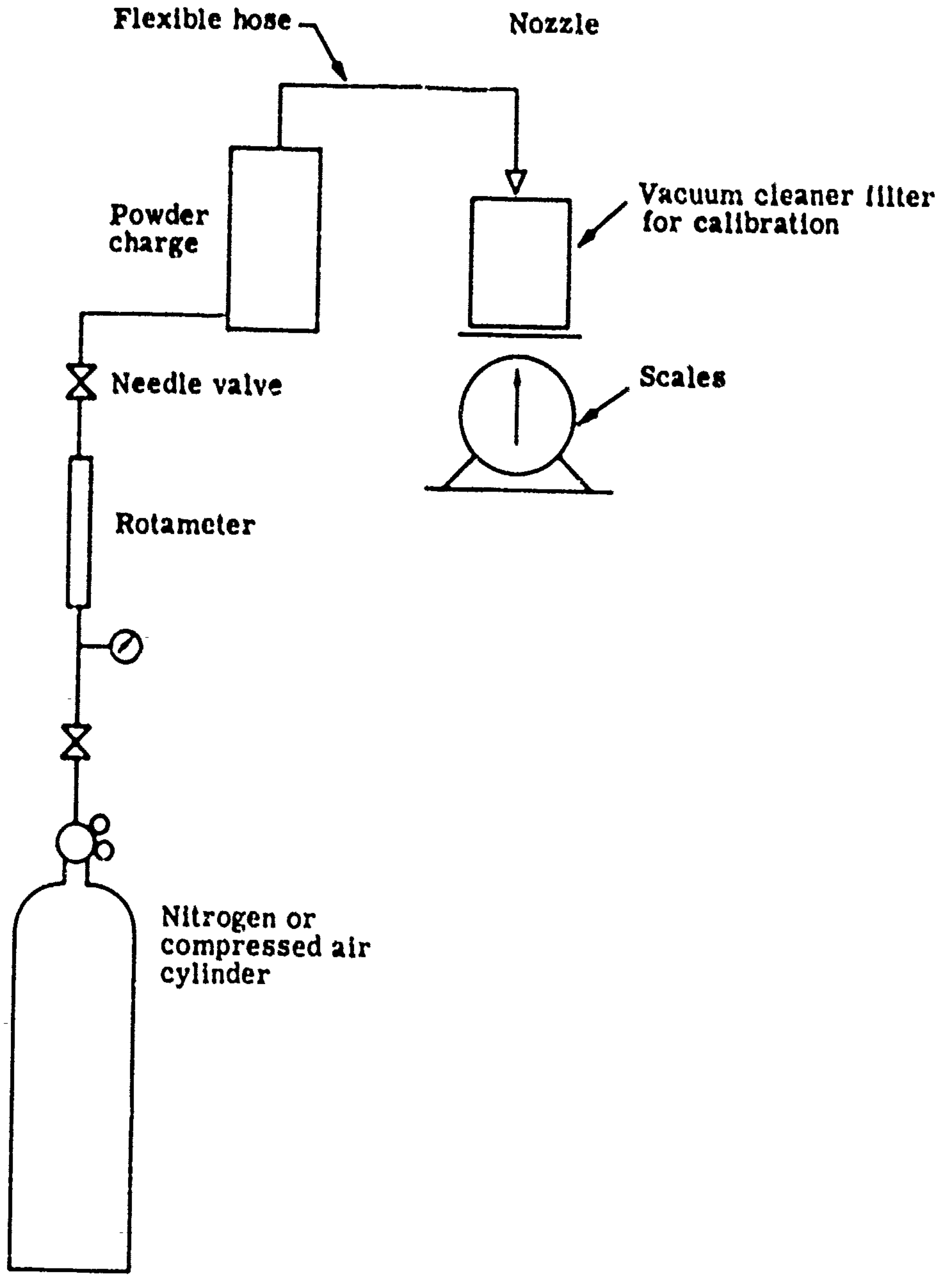

Figure 9. DRY POWDER APPLICATOR

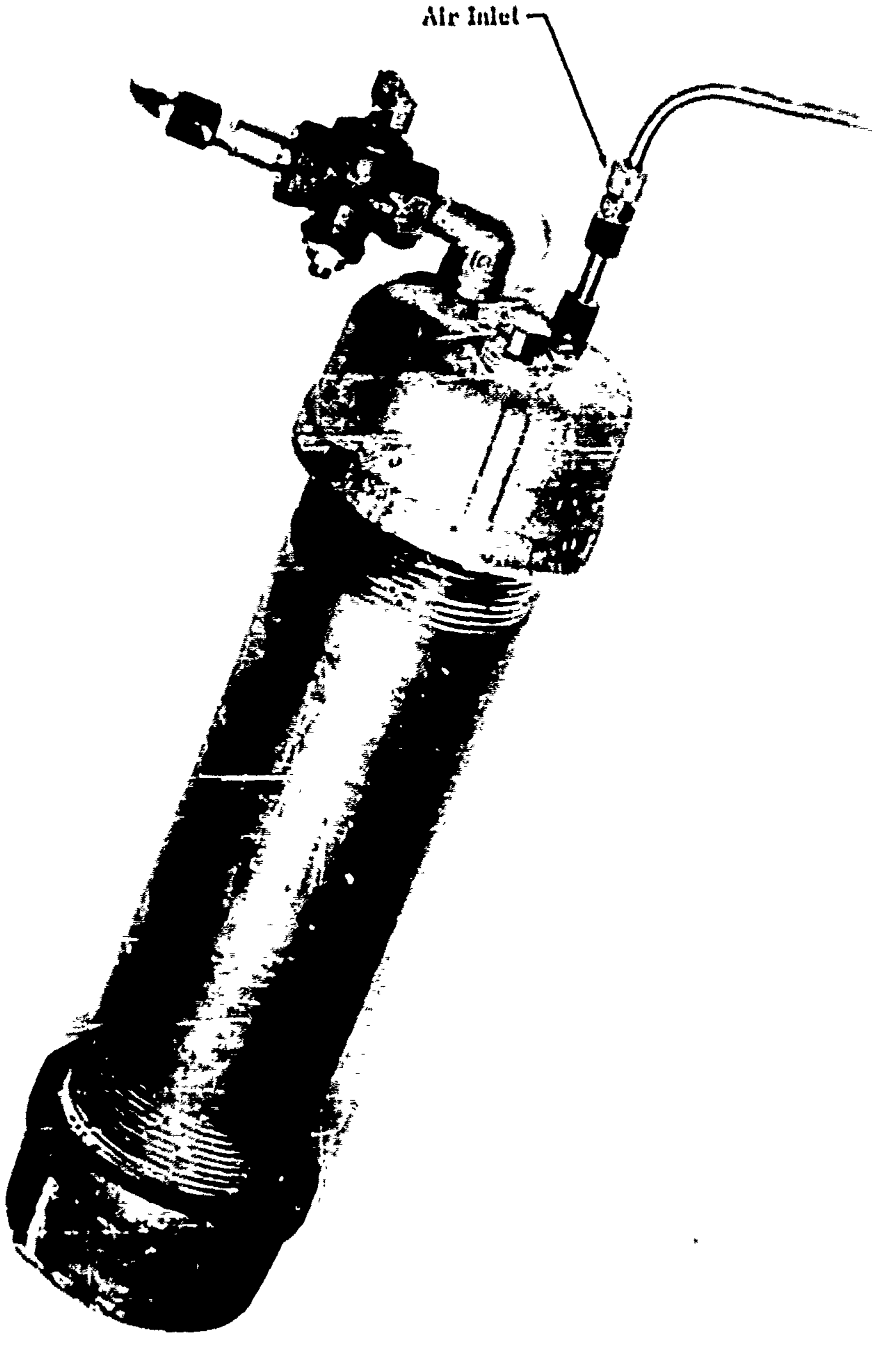

Figure 10. DRY CHEMICAL EXTINGUISHER

V. EXPERIMENTAL PROCEDURES

To evaluate an extinguishing agent, a known quantity of fuel (corresponding to about 0.1 to 0.4-in depth), was placed in the burner, allowed to reach the desired temperature, and ignited by means of a hot wire. After a selected preburn time, usually 10-sec, the agent was directed onto the fire. The length of time required for extinguishment, the amount of agent required, and the amount of propellant remaining unburned were determined as a function of agent, rate of application, application technique, and propellant. Motion picture photography was used routinely to record experimental results.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

In the discussion of the experimental results a large amount of information has been organized for logical presentation. The data have been correlated and the correlations presented in graphical form in order to present the maximum amount of information on each graph and to best illustrate the discussion. This format may obscure relationships in the basic data which are not of primary interest to this investigation and so have not been emphasized. Therefore, the basic data have been included in the appendix, making it possible for workers in the field to reinterpret these data for different purposes and to compare these results with new data as they become available.

A. CONTROL FIRES WITH ALCOHOL

Initial fires with alcohol were conducted to develop experimental techniques, to determine reproducibility, and to test the extinguishing apparatus. Table V summarizes the physical properties of the alcohols and hydrazine. Although these properties are similar, the alcohols require oxygen for combustion and hydrazine does not. This fact implies quite different combustion mechanisms.

1. Determinations of Burning Rates

Fuel was pipetted into the burner, brought to the desired temperature, and then ignited by the hot wire. Burning time was that from ignition to flame-out of the last remaining drop. Because of appreciable startup and die-down times, equilibrium burning rates could not be calculated directly. However, by varying the depth of fuel, the incremental time required to burn the additional fuel could be used to calculate a burning rate.

The burning times of methanol and ethanol fires are shown in Table VI. The incremental burning time of 170 seconds for the additional 0.093 inch of ethanol indicates a burning rate of 0.0328 in/min. Ten runs using this same incremental depth had a standard deviation of 11.5 seconds. This is high, but it is considered acceptable. The scatter is attributed mainly to variations in air flow around the burner and in the rate of flame die-down.

TABLE V

Comparison of Alcohols and Hydrazines

Fuel	Density (gm/cu cm)	Boiling Point (°C)	Heat of Combustion (kcal/mol)	Heat of Combustion cal/gm	Heat of Vaporization (kcal/mol)	Heat of Vaporization cal/gm	Heat of Combustion / Heat of Vaporization
Ethanol	0.789	78.4	327.6	7,130	9.4	204	34.9
Methanol	0.792	64.7	170.9	5,350	8.4	263	20.4
Hydrazine	1.008	113.5	146.9	4,600	9.5	300	15.3
UDMH	0.783	63.1	472.6	7,880	8.4	140	56.3

TABLE VI

Burning Times of Various Fuels

Fuel	Purity (wt per cent)	Temperature (° F)	Burning Time (sec) Depth of Pool of Fuel (in) 0.093	0.186	0.279
Ethanol	Absolute	90	218 (11.5)[a]	388	-
Methanol	Absolute	90	229 (10.5)	-	-
Hydrazine	99	140	31.1 (1.9)	38.0 (1.7)	44.4
	97	140	-	52.9 (3.4)	-
	97	195	-	35.5	-
	97	200	-	-	45.9

a. Standard deviation in seconds, $s = \sqrt{\frac{N\Sigma X^2 - (\Sigma X)^2}{N(N-1)}}$.

Note: Above data obtained from 33 alcohol and 47 hydrazine fires.

2. Extinguishment of Fires with Water

The results for water extinguishment of ethanol fires are shown in Table VII. The initial series of 27 runs were made under identical conditions. Extinguishment times varied between 20.1 and 65.0 seconds with an average of 42.4 seconds.

When ignited, the ethanol burned smoothly. After the water spray was turned on, the flame became irregular and danced over the surface. This fluctuating flame with local reignition apparently caused wide scatter in the results. A check of the spray distribution and water rate showed that these factors were constant. Adding a solenoid valve in the water line to start the spray decreased scatter slightly. A sheet of metal placed under the burner to control air flow and direct it from the sides of the burner gave very slight additional improvement.

When the fuel temperature was increased to 140°F and the preburn time to 40 seconds, frequency of reignition increased. Twenty three runs varied from 1.2 to 51.8 seconds extinguishment time. Whether the liquid remaining after the ethanol fires were extinguished could be reignited or not depended upon the time required for extinguishment and the amount of dilution with water. In those cases in which the remaining liquid could not be reignited, extinguishment was undoubtedly by dilution.

The amount of scatter in the data leads to two conclusions. First, a statistical approach must be used in evaluating each agent. This means that valid interpretations of results require a large number of laboratory extinguishments. Second, if the data scatter widely under carefully controlled laboratory conditions, the variance which can be expected in the field will be even greater. These factors must be taken into account in developing extinguishing apparatus.

B. BURNING RATES OF VARIOUS FUELS

1. Background

The burning rate of a liquid in an open pan changes with pan diameter. Since the burning rate determines the intensity of a fire

TABLE VII

Water Spray Extinguishment of Ethanol Fires

Fuel Temperature (°F)	Preburn Time (sec)	Extinguishment Time[a] (sec)	Remarks
68	20	42.4 (13)[b]	Base
90	20	34.1 (10.5)	Added solenoid valve in water line
68	20	41.1 (7)	Added sheet metal beneath burner
140	40	28.0 (14)	Higher temperature, longer preburn time

a. 0.116 gal/sq ft fuel equivalent to 0.186 inch deep.

b. Numbers in parentheses are standard deviations in seconds, $s = \sqrt{\frac{N\Sigma X^2 - (\Sigma X)^2}{N(N-1)}}$

Note: Water temperature, 68°F. Water spray rate 0.36 gpm/sq ft.
Above data obtained from 85 extinguishments.

involving any particular fuel, pan diameter is an important factor in scale-up.

Correlations developed by Blinov and Khudiakov[7] show that the amount of heat transferred from a flame to a burning liquid may be regarded as a total of that transferred by conduction, convection, and radiation. This is expressed mathematically as:

$$q = \frac{k(T_f - T_b)}{d} + U(T_f - T_b) + \sigma F(T_f^4 - T_b^4)(1 - e^{-Kd})$$

Where: q = the rate of heat transfer per unit area

k = a constant which is a function of the thermal conductivity of the pan wall and the pan geometry

T_f = the flame temperature

T_b = the boiling point of the liquid

d = the pan diameter

U = the convective heat transfer coefficient

σ = the Stefan-Boltzmann constant

F = the geometrical view factor between the liquid surface and the flame

K = the Beer's law extinction coefficient of the flame to allow for increasing opacity with thickness

Blinov and Khudiakov's experimental results indicated that a minimum burning rate occurred in pans 3 to 4 inches in diameter. In smaller pans, conduction of heat from the rim of the pan became increasingly important. In pans up to 20 inches in diameter, the increased radiation more than offset the decreased rim effect, with a corresponding increase in the burning rate. Above this diameter the burning rate was constant, indicating that the term $(1-e^{-Kd})$ had approached unity and that the radiation heat flux was a maximum.

Similar data obtained by the Bureau of Mines[8] indicate that radiation is the only significant method of heat transfer at diameters exceeding 12 inches. By assuming that F, T_f, T_b, and K remain constant and that conduction and convection are negligible, $[q = \text{constant}\ (1-e^{-Kd})]$, they

obtained generally good agreement between the calculated and experimental results, even in pans as small as 3.5 inches in diameter.

2. Comparison of Burning Rates

Burning rates were determined for hydrazine, UDMH, JP-X, and the 50:50 mixture of hydrazine and UDMH according to the procedure previously described for ethanol. The UDMH, JP-X, and 50:50 mixture fires were ignited at a liquid temperature of 80°F (well above their fire points). Burning rates for hydrazine were determined at 140°F since the fire point of hydrazine is 126°F and no fire could be maintained at a liquid temperature of 80°F. Rates of liquid regression as a function of pan size are shown on Figure 11. A reference curve for gasoline obtained by Blinov and Khudiakov[7] is shown for comparison.

All fuels which require air as an oxidizer and which burn with a diffusion flame have burning rates of the same order of magnitude. Hydrazine burns with a significantly higher rate, possibly in two stages. The first stage is a decomposition flame near the liquid surface. The second is a secondary diffusion flame of the products of hydrazine decomposition (NH_3 and H_2) with air. A value of 0.65 in/min reported by Adams and Stocks[1] for the burning rate of hydrazine in glass capillary tubes compares favorably with the values obtained in this investigation (0.48 to 1.4 in/min depending on burner dimension).

The mixture of hydrazine and UDMH burns at a rate near that of pure UDMH. The more volatile UDMH probably burns during the initial phases of the fire and the less volatile hydrazine during the final stages. The overall burning rate is still slow, however, because the hydrazine must be heated to at least 126°F before the vapor pressure is high enough to support combustion.

JP-X burned slower than either of the hydrazine fuels. The flame was orange and smokey. A tarry residue remained after combustion.

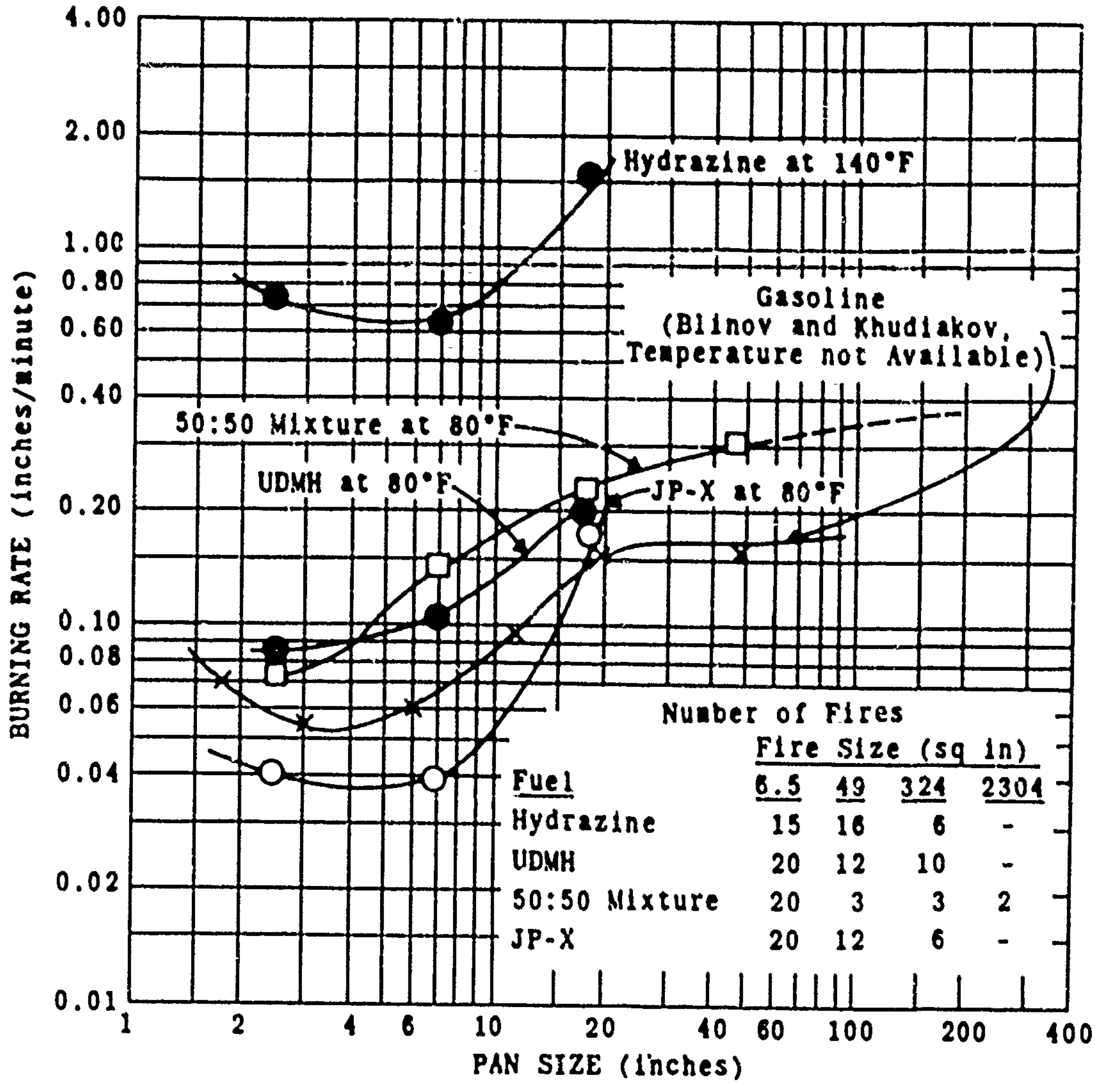

Figure 11. BURNING RATE VERSUS PAN SIZE FOR VARIOUS FUELS IN SQUARE PANS

3. Effect of Pan Size

Because of the mechanism of heat transfer discussed in the preceding section, the burning rates of the fuels in the 49-sq in pan were not much different than those in the 6.5-sq in pan. The increased heat transferred by radiation was offset by the decrease in heat transferred by conduction.

Although the flames from the 49-sq in fire extended one foot above the liquid, those from the 324-sq in fire extended six feet. This large increase in flame size increased the radiant heat flux and resulted in increased burning rates for the fuels in the 324-sq in pan.

The 50:50 mixture was the only fuel burned in the 2304-sq in burner. The fact that the burning rate of the mixture in this burner was faster than in the 324-sq in burner indicates that still larger fires are required before the maximum rate is reached. However, if the data from the 324-sq in and 2304-sq in burners are used to define the theoretical curve according to the Hottel relationship, the maximum asymtotic burning rate is 0.375 in/min. The burning rate of the mixture in the 2304-sq in burner is 87 per cent of this maximum value.

Since there is both a decomposition and a diffusion flame, the hydrazine presents a total anomoly in the prediction of the scaling of pan fires. If the controlling mechanism is the decomposition flame of hydrazine burning close to the surface of the liquid, then the preinduction zone represented by the distance between the liquid and the flame front should be relatively insensitive to burner size (unless the burner size approached this flame-to-liquid distance). The burning rate should therefore be independent of fire size. If radiation is the controlling mechanism and the radiation effect were of the same order as for the other fuels, its contribution should only be in the range of 10 per cent of that actually measured for hydrazine. The fact that hydrazine indicates a scale behavior similar to diffusion flames, but having a burning velocity ten times as large indicates that serious deficiencies still exist in our understanding of the behavior of fires. It would be of interest to conduct similar experiments using a carbon-containing fuel such as ethylene or propylene oxide which can also support either a decomposition flame or a normal flame.

Conclusions are as follows:

(1) The burning rate of hydrazine is significantly higher than that of the other fuels because of its monopropellant properties.

(2) Although the 6.5-sq in pan is useful for screening tests, it is not satisfactory for scaling data because the method of heat transfer is different from that of larger fires.

(3) Useful scaling data can be obtained from the 49- and 324-sq in pans, but the use of a larger pan is also indicated.

(4) Data obtained using the 2304 sq in fires should be adequate for determination of extinguishment requirements of even larger fires.

C. EXTINGUISHMENT OF PROPELLANT FIRES

1. Hydrazine Fires

a. Water Sprays

The mechanism by which water sprays extinguish hydrazine fires is dilution of the hydrazine to a concentration which will not support combustion. Since dilution is the extinguishment mechanism, the most satisfactory correlation of variables was obtained by normalizing the spray rate per unit volume of fuel, i.e., gal water/sec per gal fuel. As shown in Figure 12, when water was applied to 6.5-, 49-, and 324-sq in hydrazine fires at rates of 0.01 to 0.33 gal water/sec per gal of fuel (0.2 to 1.2 gpm/sq ft), the hydrazine concentration after extinguishment indicated a dilution to between 40 and 70 weight per cent. The residues from extinguishment of the larger fires were more dilute than those from the smaller fires. In the larger fires, more heat radiated to the liquid and increased the temperature; therefore, more dilute solutions supported combustion.

The concentration of hydrazine in the residue after extinguishment decreased as the depth of the fuel decreased. Decreasing depth is indicated by increasing normalized water spray rate in Figure 12. Since water and hydrazine have approximately the same densities, concentration gradients are easily established. Mixing depends mostly on the depth of the pool and

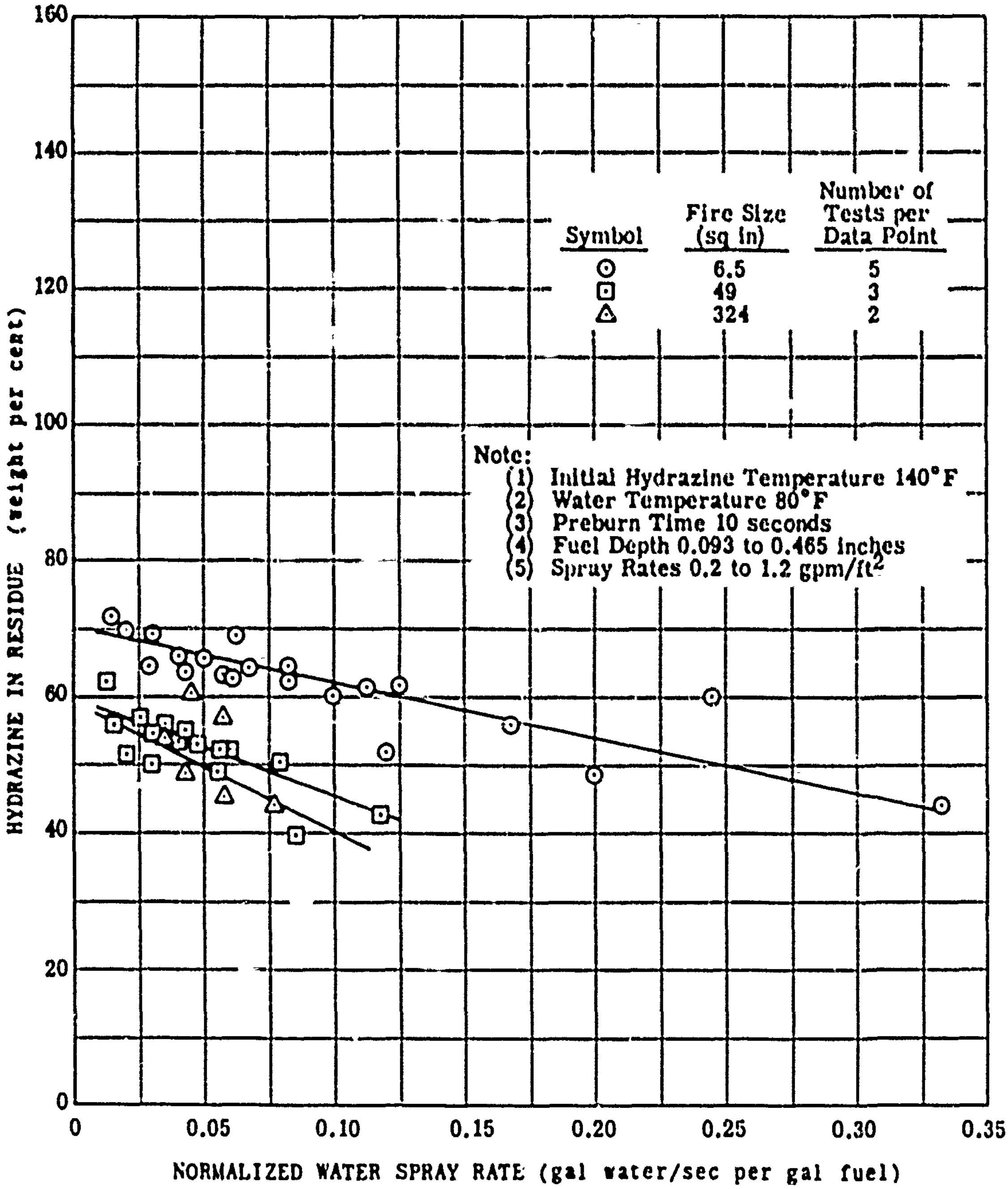

Figure 12. CONCENTRATION OF HYDRAZINE IN RESIDUE REMAINING AFTER EXTINGUISHMENT OF HYDRAZINE FIRES BY WATER SPRAY

the force with which the water spray hits the surface. Both effects decreased the concentration of hydrazine in the residue as the normalized spray rate increased.

Since the mechanism of extinguishment is primarily dilution, in ideal cases the time for spray to extinguish fires should be directly proportional to the amount of fuel present and inversely proportional to the rate of application of spray. However, the simplicity of the dilution mechanism is complicated by the following factors:

(1) As the fire progresses, some of the fuel is consumed. Only the remainder is diluted.

(2) Some of the water which does reach the burning liquid is later vaporized.

(3) Some of the water vaporizes in the flame and never reaches the burning liquid.

(4) Mixing of the water and fuel is not instantaneous.

Because of these factors, the length of time that spray must be applied is not directly proportional to the volume of fuel or the inverse spray rate. However, as shown in Figure 13, the data may be correlated by plotting the logarithm of the extinguishment time versus the logarithm of a normalized rate of application of spray (gal water/sec per gal of fuel). In view of the above complicating factors, the fact that even an empirical correlation can be obtained is indeed fortuitous. The slopes and intercepts of the curves would be expected to be complex functions of the properties of the fuel, pan size, and agent. The main conclusion from the curves is that larger fires require a longer application of spray before extinguishment for the same normalized spray rate. The increased time, however, is slight compared to the increased fire size.

The percentage of original fuel remaining after extinguishment, a measure of extinguishment efficiency, is presented in Figure 14 as a function of the rate of application of water. Faster rates and deeper pools resulted in greater efficiencies.

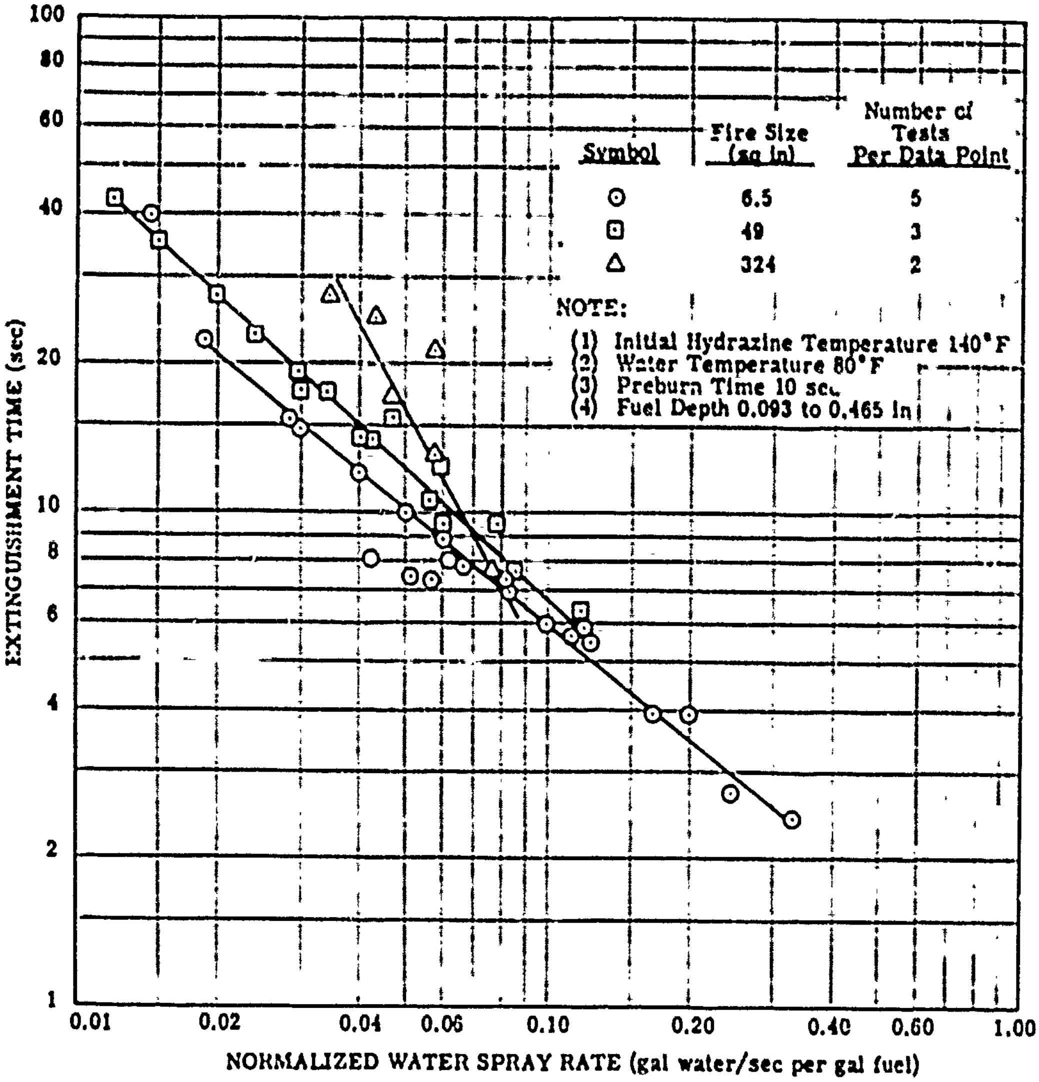

Figure 13. EFFECT OF NORMALIZED SPRAY RATE ON EXTINGUISHMENT TIME OF HYDRAZINE FIRES

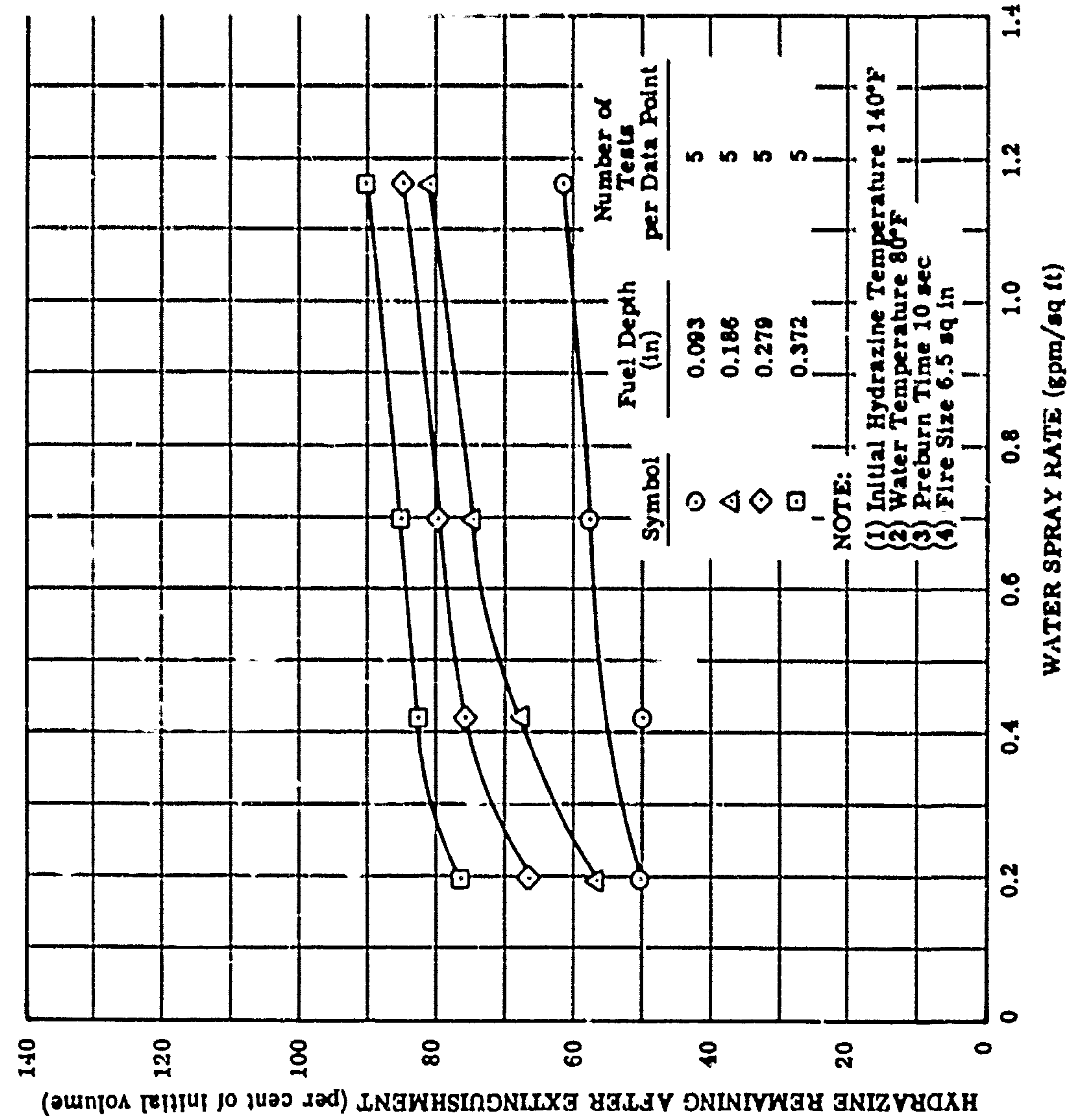

Figure 14. EFFECT OF WATER SPRAY RATE ON AMOUNT OF HYDRAZINE REMAINING AFTER EXTINGUISHMENT

Because dilution is the mechanism by which water sprays extinguish hydrazine fires, the major scaling factor for extinguishment is a function of the amount of fuel present. It is not a function of diameter, per se. Spray rate, liquid depth, and fire diameter influence scale-up slightly. Since dilution to 50 weight-per cent appears adequate, the amount of water required for extinguishment is about 1 gal per gal of fuel. Any vertical concentration gradients or consumption of fuel reduces the amount required. Conversely, any vaporization of water in the flame increases the amount of water required.

b. Fog

As shown in Figure 15, measurements with the 6.5-sq in burner indicated that water fog was less effective than coarse water sprays against hydrazine fires. Since the concentration of hydrazine remaining after extinguishment was about equal to the spray results (Figure 16), increased vaporization of the fine droplets in the flame probably lowered extinguishment efficiency. Fog was less effective against 49-sq in fires than against 6.5-sq in fires, again because vaporization in the flame prevented liquid dilution. The fact that as much as 1.5 gal of water per gal of fuel originally present were required for extinguishment, in comparison to 0.5 gal/gal for spray under the same conditions, indicates the magnitude of the vaporization, especially since most of the fuel originally present was consumed in the fire.

Fog is not a good extinguishing agent for hydrazine fires and would probably fail to extinguish very large fires.

c. Gentle Spray and Solid Stream of Water

Figure 17 shows the results of extinguishments in the 6.5 sq in burner using gentle application of water spray and a solid stream of water as compared to the previous results using a forceful vertical spray and fog. The forceful vertical spray extinguished the fires best.

The same nozzle was used to apply the forceful vertical and gentle sprays, but the gentle spray was applied from a horizontal direction

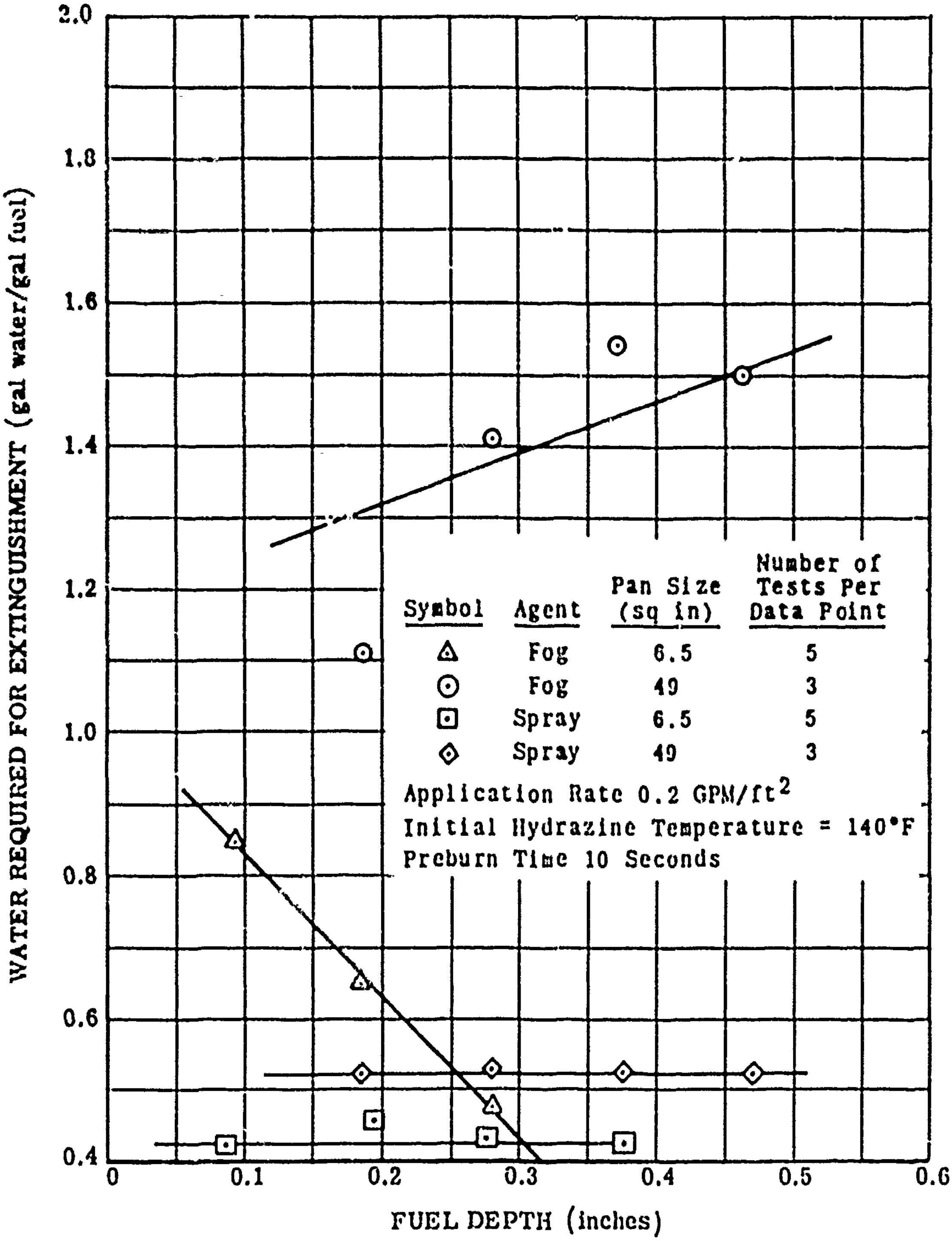

Figure 15. EXTINGUISHMENT OF HYDRAZINE FIRES BY WATER FOG—WATER REQUIRED VERSUS FUEL DEPTH

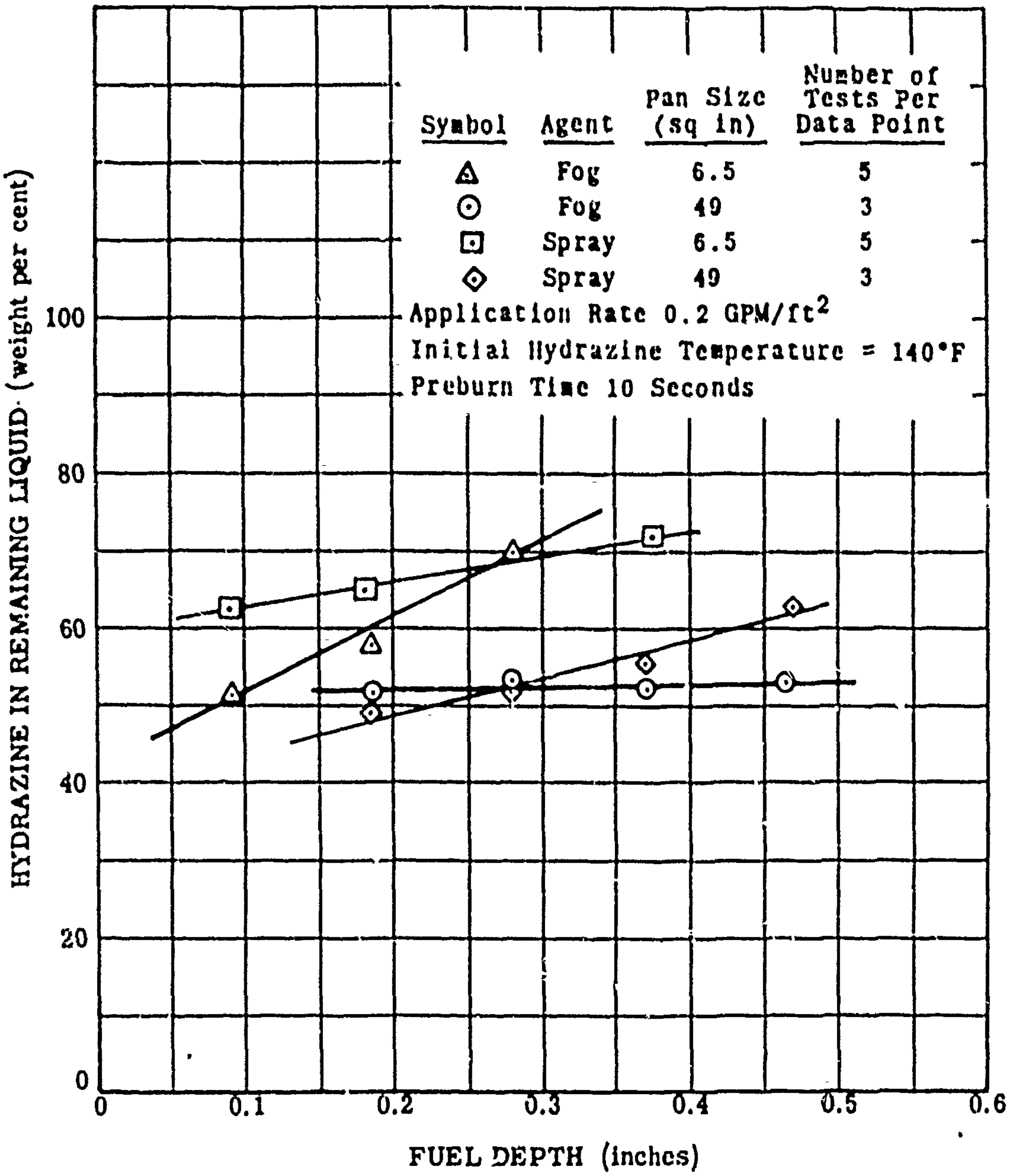

Figure 16. EXTINGUISHMENT OF HYDRAZINE FIRES BY WATER FOG—FINAL HYDRAZINE CONCENTRATION VERSUS FUEL DEPTH

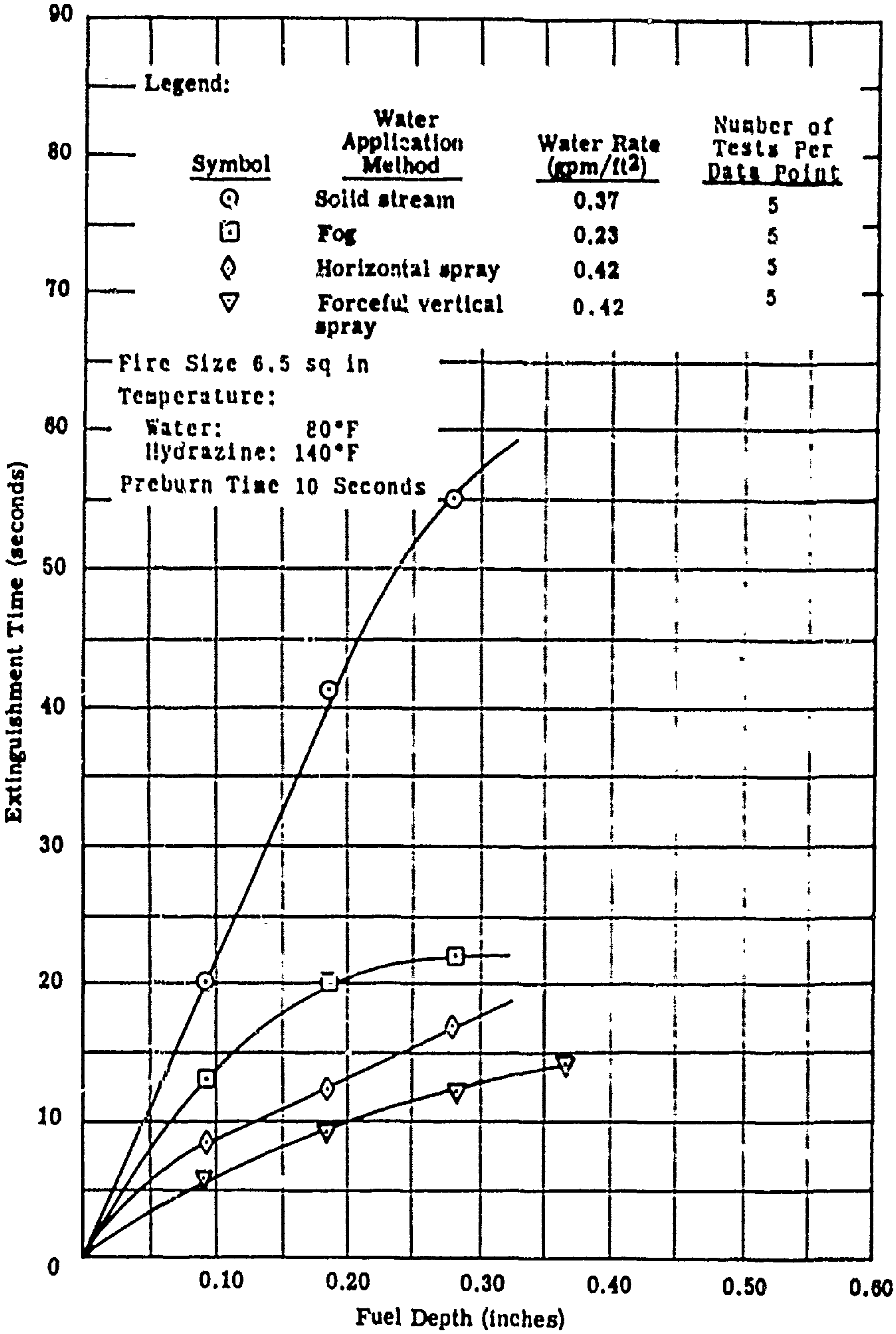

Figure 17. EFFECT ON EXTINGUISHMENT TIME OF VARIOUS METHODS FOR APPLYING WATER TO HYDRAZINE FIRES

so that the droplets fell gently onto the burning liquid. The solid stream of water was brought into one corner of the burner; with no attempt to play the stream over the surface.

Since the gentle spray and the fog droplets had a longer residence time in the flame zone, more evaporation from the droplets occurred and less water reached the burning liquid. In addition, the water which did reach the liquid was probably hotter than that from the vertical spray and had a smaller cooling effect. Since the spray was composed of larger droplets, it was more effective than the fog.

Figure 18 shows the concentration of the hydrazine remaining after extinguishment for the various methods of water application. There was little evidence of a steeper concentration gradient when using the gentle application techniques. For example, the concentration of the remaining hydrazine after the fog extinguishment was comparable to that after vertical spray extinguishment. Hydrazine concentration, following extinguishment by the horizontal spray, was lower. This may be explained by the fact that since the extinguishment time was longer, more heat could be transferred back to the liquid and a greater dilution would be required at extinguishment. In the case of the solid stream of water, little mixing occurred so that horizontal gradients existed with the fuel-rich areas supporting combustion. Since 45 weight per cent hydrazine is the lowest concentration which supports combustion, the average concentration of 22 weight per cent for this case indicates the magnitude of the horizontal gradients.

These results from the small burner indicate that a forceful application of a spray is the best method of applying water to a hydrazine fire because it extinguished the fires quicker and less water was required. Therefore, this application technique is emphasized in the work on the other fuels, and in the larger fire sizes.

d. Dry Chemical

A modified sodium bicarbonate powder (50 microns average particle size) was very effective in extinguishing fires involving hydrazine and air. As seen in Figure 19, when as little as 0.016 lb/sec per sq ft was applied, the

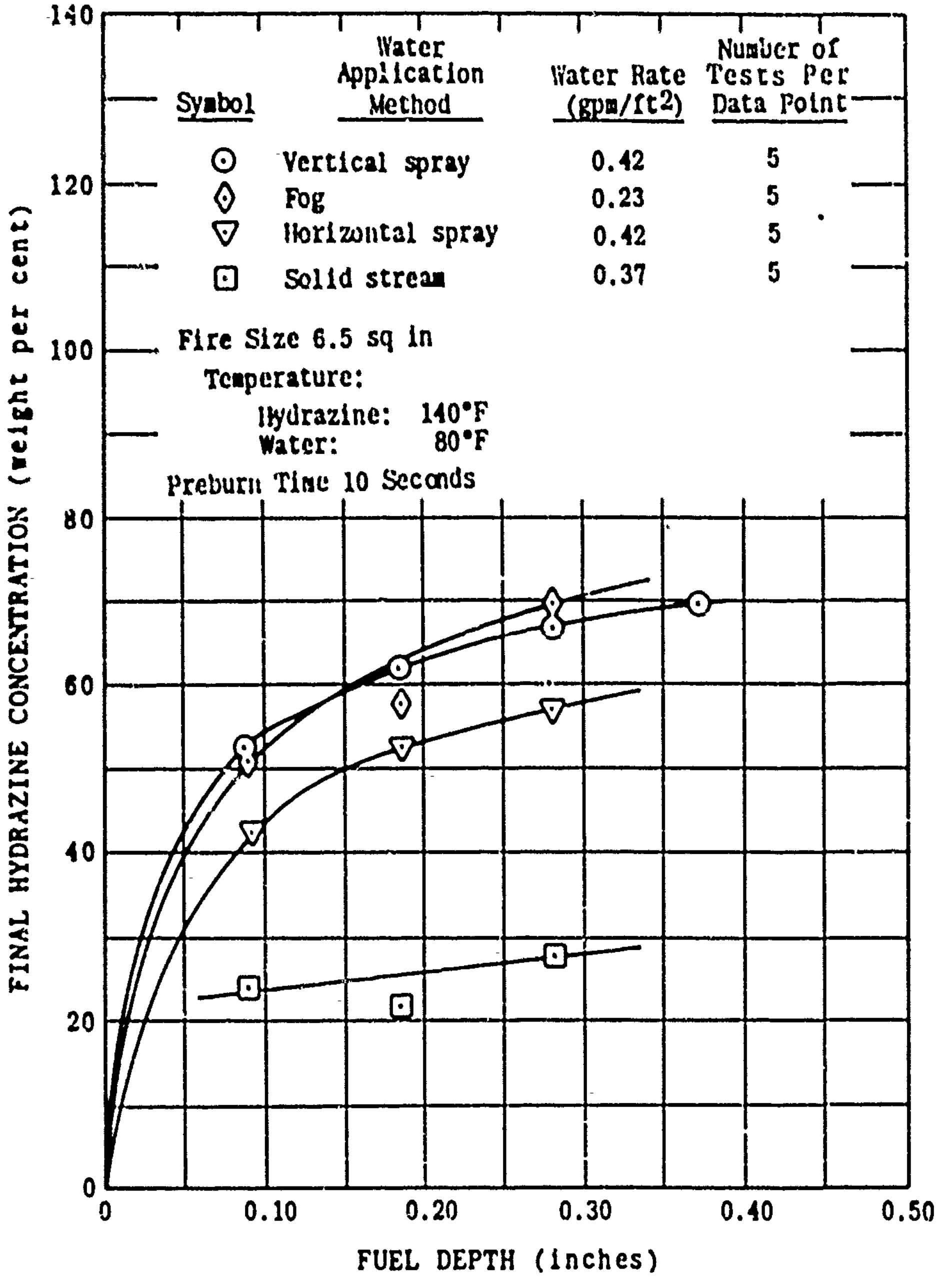

Figure 18. EFFECT ON REMAINING HYDRAZINE CONCENTRATION FOR VARIOUS METHODS OF WATER APPLICATION

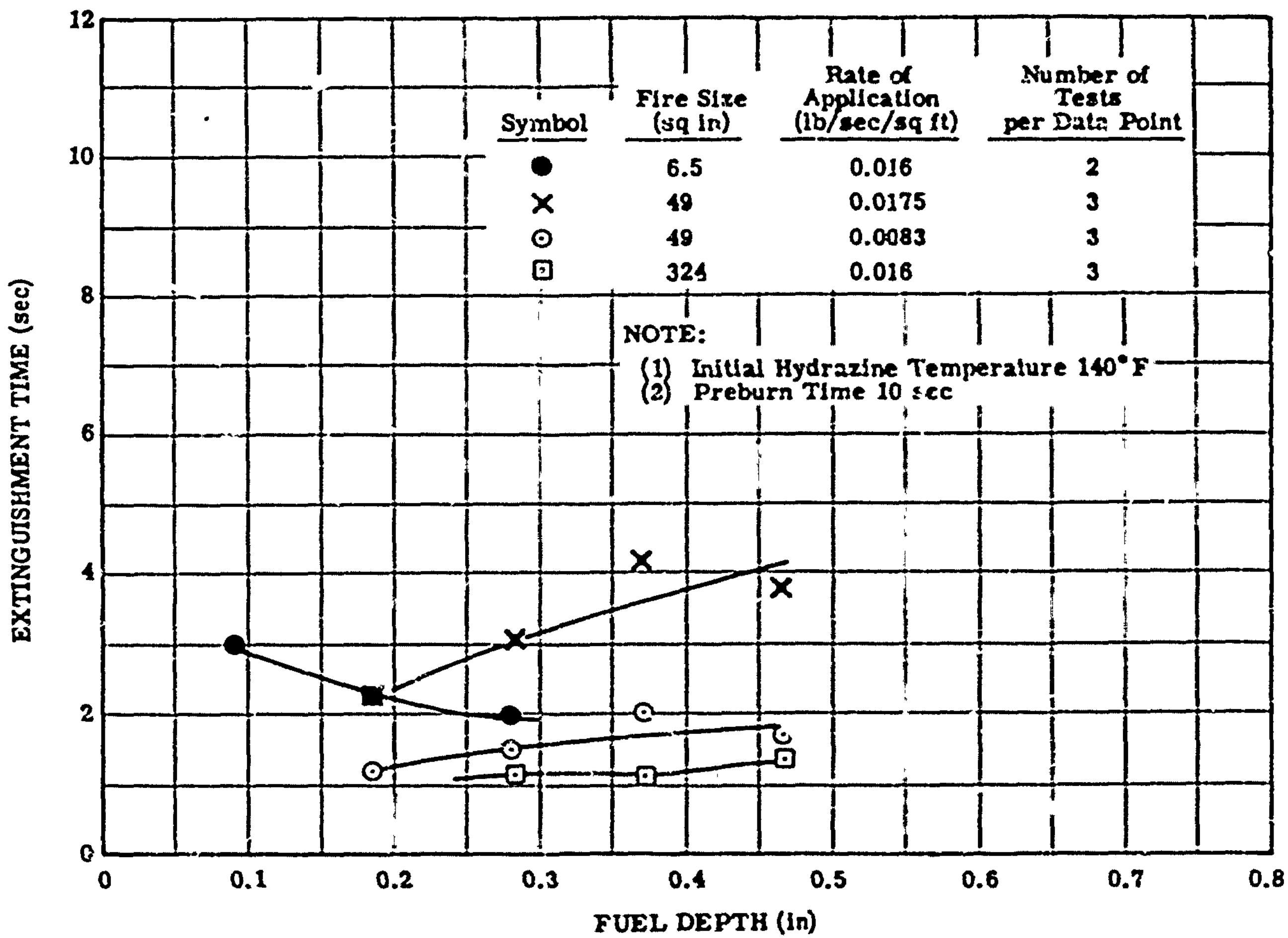

Figure 19. EFFECT OF FUEL DEPTH ON EXTINGUISHMENT TIME OF HYDRAZINE FIRES BY SODIUM BICARBONATE

fires extinguished in less than four seconds. The depth of burning liquid had no observable effect, but the burning surface had to be completely covered to produce extinguishment. This requirement probably caused the apparently anomalous result that more time was required for extinguishment at the faster application rate. These results are similar to those obtained in the 6.5- and 324-sq in burners, in which 0.016 lb/sec per sq ft extinguished the fires in less than three seconds. After extinguishment, the fires could be reignited by the hot wire. In practice, therefore, some other agent such as water might have to be applied after the dry chemical to prevent reignition after extinguishment.

A solution of 8 per cent by weight of sodium bicarbonate in water applied as a water spray at a rate of 0.6 gpm/sq ft showed no improvement over water as an extinguishing agent in the 6.5-sq in burner. This is consistent with other work which has shown that extinguishment by dry chemical involves reactions in the flame.

A potassium bicarbonate powder (25 microns diameter) was as effective as the sodium bicarbonate. However, an ABC type powder was ineffective against the hydrazine fires.

Scale-up in dry chemical extinguishment is a function of fire area. Good results with this agent require complete blanketing of the fire to prevent flashover from reigniting the extinguished areas. Dry chemicals are attractive in that they can extinguish the fires in a comparatively short time with minimum weight of agent.

e. Foam

Foam* effectively extinguished hydrazine fires. Alkaline hydrazine rapidly destroyed the foam to form a surface layer of water which spread over the burning fuel. The water diluted the hydrazine and protected the upper foam layers from the destructive hydrazine vapors. Fresh foam then spread over the water layer and, if it was completely covered, extinguished the fire. The minimum foam depth was about 1 inch.

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* A 6% alcohol-type foam was used at a 10:1 expansion ratio.

Results of extinguishment experiments for three sizes of fires are shown in Figure 20. Because of the variability in blanket thickness which is effected by foam fluidity, stability, and support by the sides of the pans, a consistent correlation for various fire sizes was not obtained.

As the depth of fuel increased, more foam was required for extinguishment. However, there is apparently a maximum fuel depth (depending on the thickness of the water rich layer) above which the amount of foam required for extinguishment is constant. Results indicate that this maximum depth increases with greater fire sizes. It is about 0.3 inch, greater than 0.45 inch, and 0.7 inch for 6.5-, 49-, and 324-sq in fires, respectively.

Even though greater application rates increased foam effectiveness, three different sizes of fires required approximately the same quantity of foam per unit area, i.e., 0.06 to 0.10 gal liquid/sq ft. Therefore, it appears that the scaling factor is constant for extrapolation of results to large fires involving various depths of fuel. The absolute quantity of foam required would be directly proportional to fire area.

Figure 21 illustrates the variations of the concentration of hydrazine remaining after extinguishment with initial fuel depth. Although the concentrations of remaining hydrazine decreased as the foam blanket collapsed after extinguishment, the fact the final hydrazine concentration can reach 86 weight per cent shows that concentrations gradients are very steep. These data also confirm that surface dilution is the extinguishment mechanism.

It is concluded that the alcohol-type foams are satisfactory agents for extinguishment of hydrazine fires. The quantity of foam required per unit area depends on the structure of the foam and the geometry of the fire. The foam should be evenly distributed over the surface and applied as fast as possible. Fluid foams are recommended to minimize the thickness of the extinguishing blanket. Experience with other hydrazine-type fuels indicates that ordinary mechanical foams are not satisfactory agents because they break down too rapidly when they contact hydrazine.

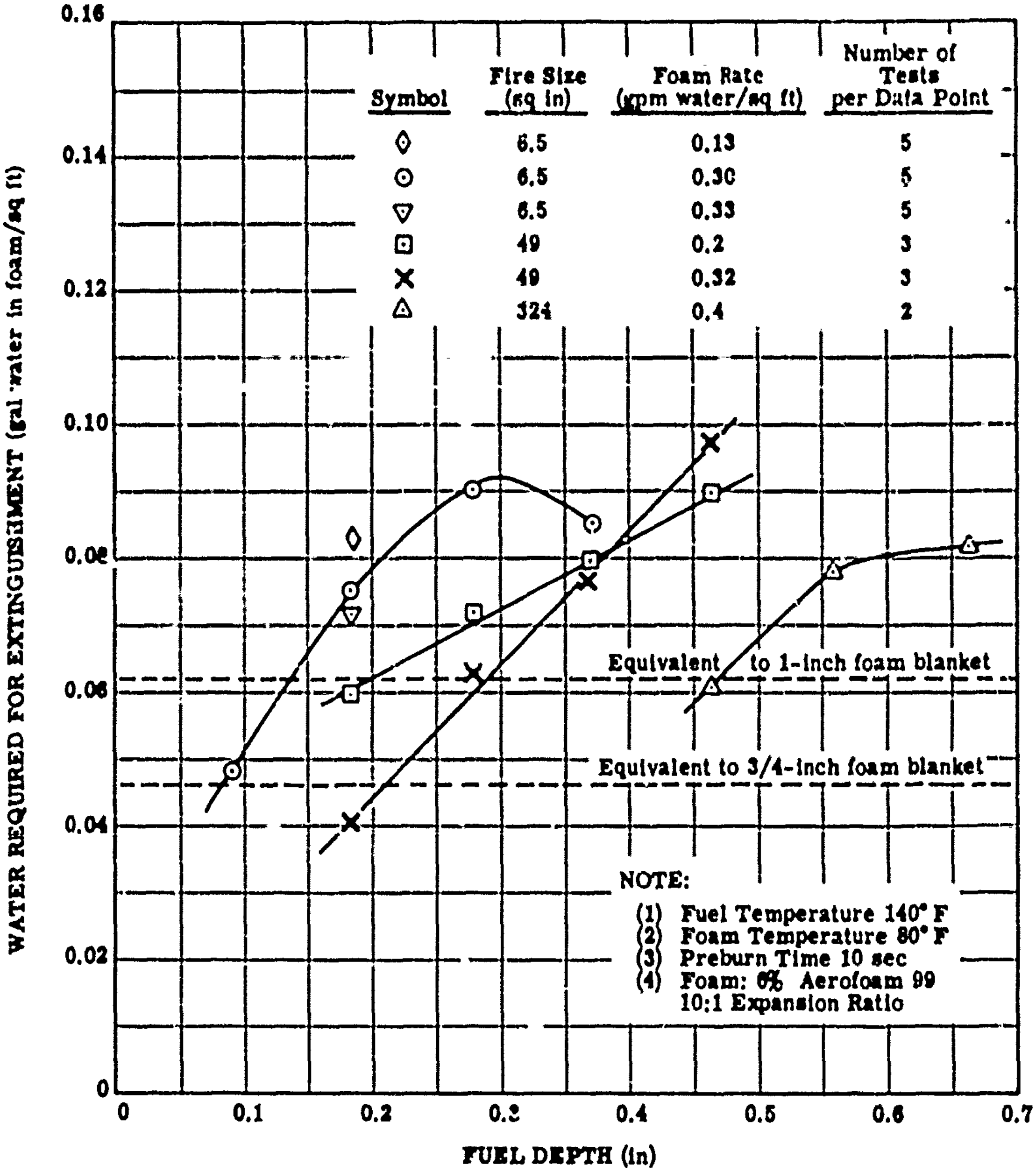

Figure 20. THE EFFECT OF FUEL DEPTH ON AMOUNT OF FOAM REQUIRED TO EXTINGUISH HYDRAZINE FIRES

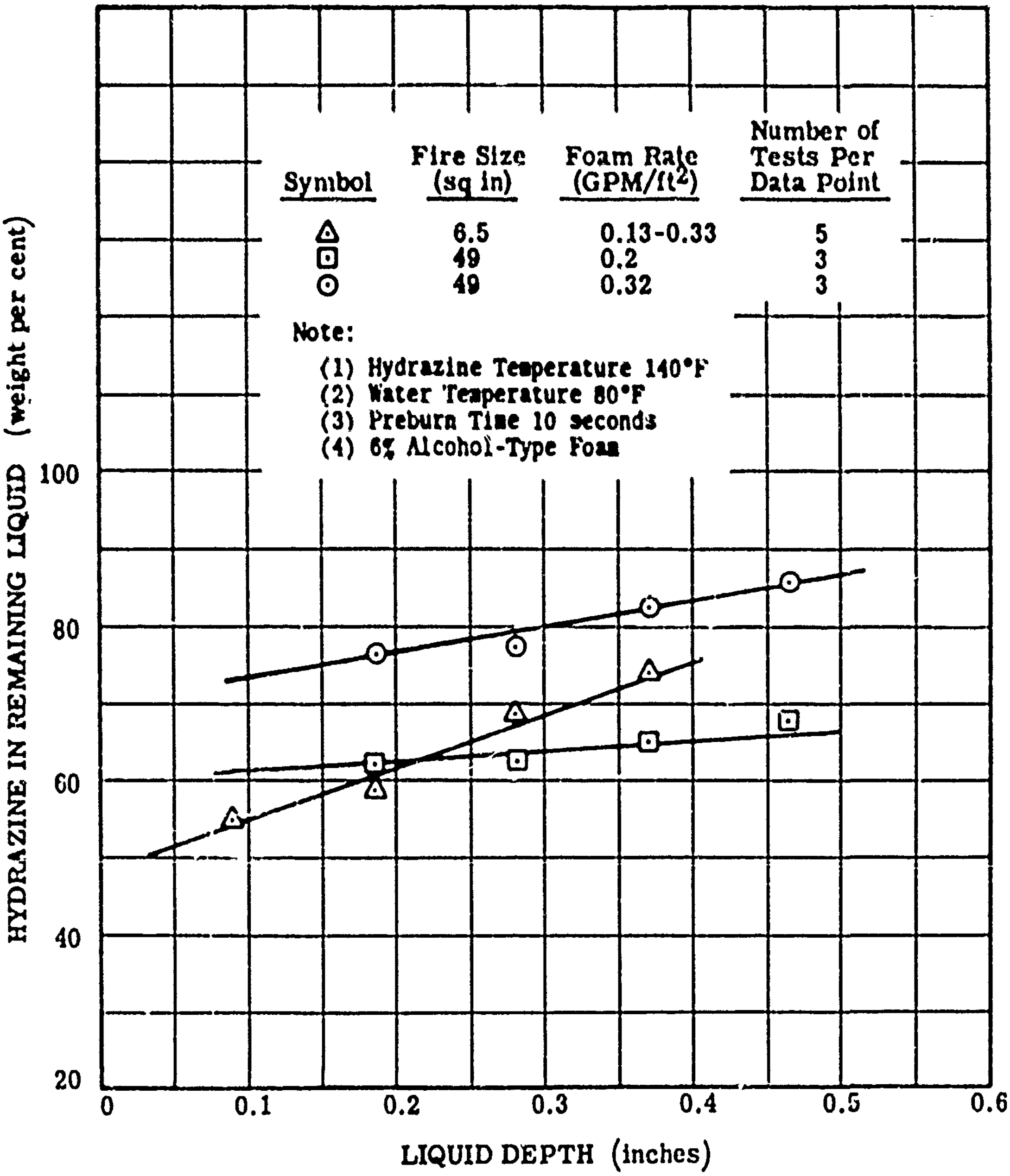

Figure 21. EFFECT OF LIQUID DEPTH ON CONCENTRATION OF HYDRAZINE REMAINING AFTER EXTINGUISHMENT OF HYDRAZINE FIRES BY FOAM

f. Chlorobromomethane

Chlorobromomethane (CB) was sprayed on hydrazine fires at a rate of 0.11 gpm/sq ft through the nozzles also used for water spray. The CB reacted with the hydrazine, increased the intensity of the fire, and produced dense white fumes. The fires continued to burn until hydrazine was consumed. CB was ineffective as an extinguishing agent for hydrazine fires under these conditions.

g. Investigation of Other Extinguishing Agents

Several chemicals besides those already discussed were tested for inhibition of hydrazine-type fuel combustion.

Aniline can trap $NH_2\cdot$ radicals which are believed to be intermediates in the combustion mechanism. When 2 per cent aniline was added to hydrazine, burning rate decreased 10 per cent; too small an effect to be useful.

When an 8 per cent sodium bicarbonate solution was used as spray, no improvement over pure water spray was observed.

A solution of 20 grams of potassium iodide and 100 grams of hydrazine was burned to test inhibition. Although burning rate greatly decreased as a molten slag formed on top of the burning liquid, all of the hydrazine burned. Addition of 10 per cent boric acid (contained in some ABC powders) behaved similarly.

When an inert silicone oil blanketed the surface of burning hydrazine, the fire was not extinguished.

2. Summary of Hydrazine Fires Extinguishment and Comparison with Other Fuels

a. Water

Water applied rapidly as a forceful, coarse spray, and directed toward the base of the flame, is recommended. A minimum total amount of 1.0 gal of water (distributed uniformly) per gal of fuel is required to insure extinguishment. This value is significantly less than the 2.0 or 2.5 gal per gal of fuel required to extinguish fires of the 50:50 hydrazine:UDMH mixture or pure UDMH.

b. Dry Chemical

Dry chemicals extinguished hydrazine fires more rapidly than any other agent. About 0.04 lb/sq ft is required. Extinguished fires can be reignited, however, by either a hot source or N_2O_4 vapors. Water is recommended as an auxiliary agent applied after extinguishment to eliminate this hazard. The minimum requirement of 0.04 lb/sq ft is less by a factor of 2.5 than the 0.1 lb/sq ft required to extinguish fires of pure UDMH, JP-X, or 50:50 hydrazine:UDMH.

c. Foam

Foam effectively extinguished hydrazine fires when 0.1 gal of contained liquid per sq ft of fire was applied. For fuel depths greater than 0.16 inch, less water is required in a foam than in a water spray. However, because water spray can be more easily applied, it will probably be more desirable as an extinguisher unless very deep pools of fuel are involved or, because of a limited supply, water must be used most efficiently.

The minimum requirement of 0.1 gal/sq ft is about 30 per cent less than the 0.15 gal/sq ft required to extinguish fires of JP-X, or 50:50 hydrazine:UDMH, and 40 per cent less than the 0.25 gal/sq ft required for UDMH fires.

d. Other Agents

Other agents investigated are not considered effective against hydrazine fires. Water applied as fog or a solid stream, chlorobromomethane, or ABC-type dry chemical agents are not considered effective against hydrazine fires.

3. UDMH Fires

a. Water Sprays

As was the case with hydrazine fires, the length of time that water sprays had to be applied before extinguishment of UDMH fires was a function of the amount of fuel present and the rate of application of the

spray. This indicates that the mechanism of extinguishment of UDMH fires is also one of dilution of the burning liquid to a concentration below which it will not support combustion. The UDMH fires required a longer application of spray than did the hydrazine fires because more dilute solutions of UDMH will support combustion and the UDMH burns at a slower rate.

Figure 22 shows that the fires in the 6.5-, 49-, and 324-sq in burners were extinguished when the UDMH concentration was reduced to approximately 30 weight per cent. This final concentration was the same for all spray rates, pan diameters, and liquid depths. Since water is more dense than UDMH, it is believed that good mixing occurred as the water settled through the UDMH.

These results are consistent with Figure 23, which shows on the basis of the fire points of UDMH and hydrazine solutions, that UDMH fires support combustion at much lower temperatures and concentrations. Consequently, UDMH fires are more difficult to extinguish.

As was the case with the hydrazine fires, the larger fires required a longer application of spray before they were extinguished, see Figure 24. Since the concentrations of UDMH remaining in the residue after extinguishment were similar, regardless of fire size, the increased vaporization of the water droplets in the larger flames appears to increase the amount of water required.

The percentage of UDMH remaining after extinguishment as a function of spray rate is presented in Figure 25. Faster spray rates are more effective than slower rates for extinguishing UDMH fires. There was little or no change in the percentage of fuel remaining after extinguishment as the depth of UDMH increased. This indicates that a basic difference in extinguishment behavior arises from the more complete and rapid mixing of water with UDMH than with hydrazine.

In a spill-type configuration, water should be directed toward the base of the fire to minimize water evaporation in the flame and evenly distributed over the entire surface of the burning UDMH.

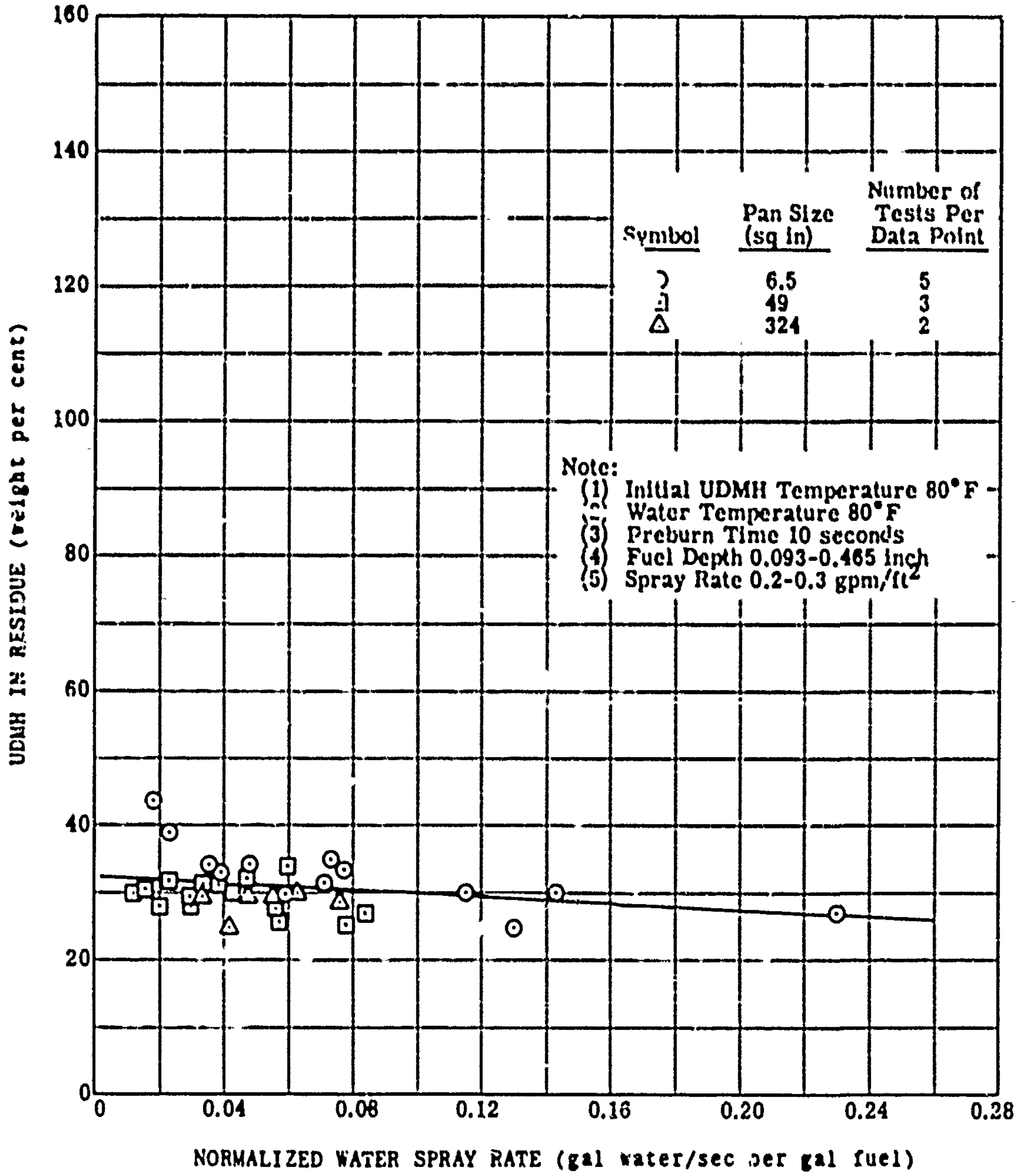

Figure 22. CONCENTRATION OF UDMH IN RESIDUE REMAINING AFTER EXTINGUISHMENT OF UDMH FIRES BY WATER SPRAYS

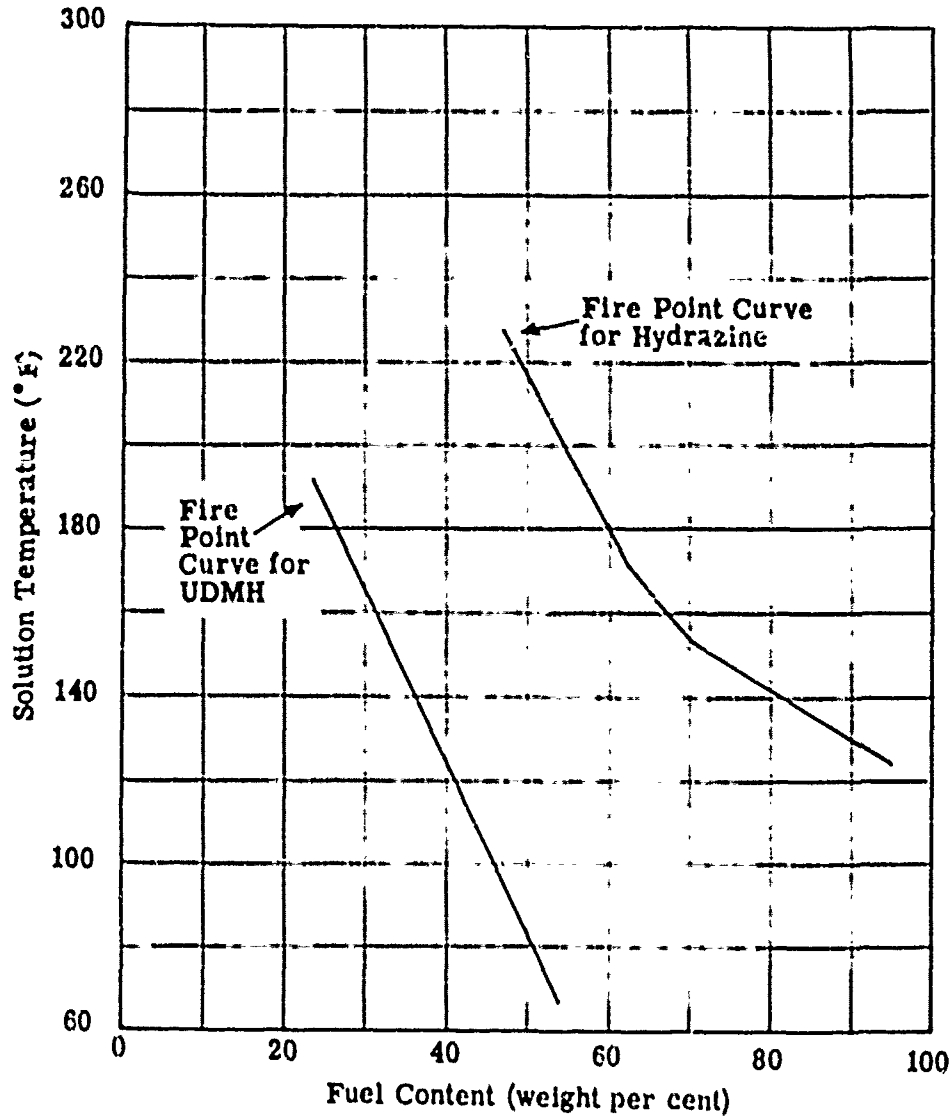

Figure 23. FIRE-POINT CURVES OF HYDRAZINE AND UDMH-WATER SOLUTIONS

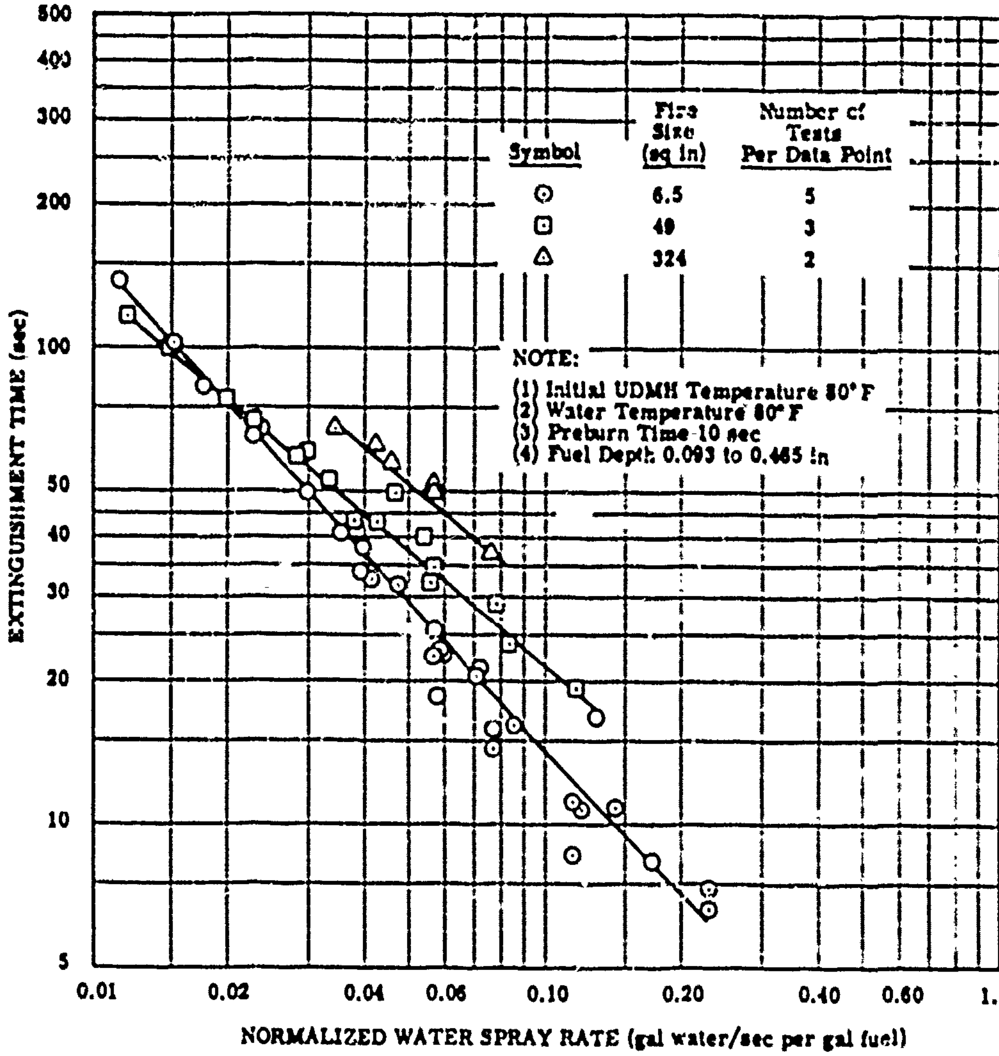

Figure 24. EFFECT OF NORMALIZED WATER SPRAY RATE ON EXTINGUISHMENT TIME OF UDMH FIRES

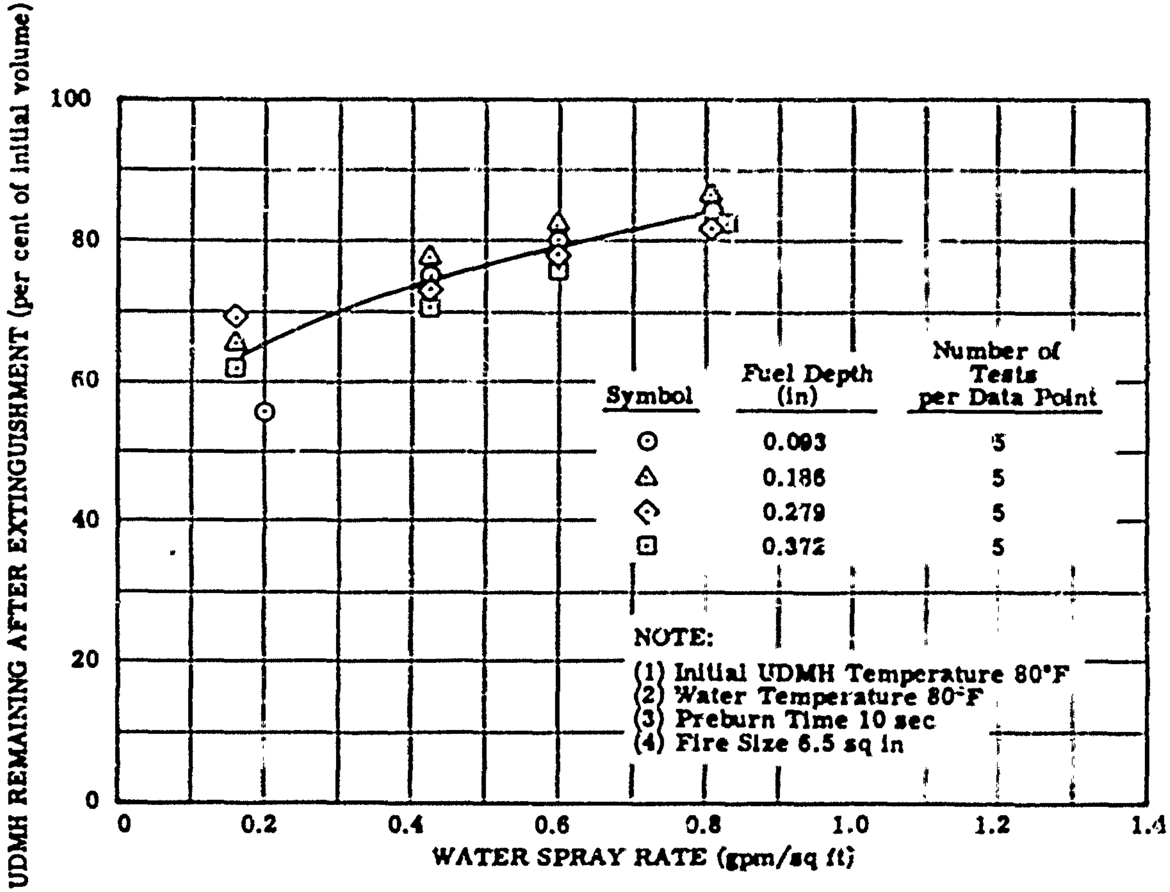

Figure 25. EFFECT OF WATER SPRAY RATE ON AMOUNT OF UDMH REMAINING AFTER EXTINGUISHMENT

b. Fog

Fog extinguished UDMH fires by the same mechanism as water sprays, i.e., dilution. Because of the finer drop size, more water was required because of losses by vaporization in the flame. Fog applied at a rate of 0.2 gpm/sq ft to the 49-sq in fires required 2.13 gal per gal of UDMH compared to 1.46 gal per gal of UDMH for water spray at the same rate. Fog is not a promising agent for use against UDMH fires.

c. Dry Chemical Powders

Dry, powdered sodium bicarbonate rapidly extinguished UDMH fires. Results of tests on three fire sizes are summarized in Table VIII.

TABLE VIII

Extinguishment of UDMH Fires with Dry Powder

Fire Size (sq in)	Application Rate (lb/sq ft-sec)	Time to Extinguish (sec)
6.5	0.094	2
49	0.0175	< 2
	0.0083	< 2
324	0.016	5.2

These results show that dry powder extinguished UDMH fires slightly less effectively than it did hydrazine fires. Also, it was more effective for small fires.

If the fuel was not completely covered, fire spread over the surface when the flow of powder stopped. In every case a hot wire could reignite the UDMH after extinguishment.

Dry powder is considered very effective against UDMH Fires. It is particularly suitable for rapid extinguishment of small fires when a minimum amount of agent must be applied. However, it should be followed by water dilution to prevent reignition.

d. Vaporizable Liquid Agents

As shown in Table IX, trichlorotrifluoroethane* extinguished 6.5-sq in UDMH fires when applied at a rate of 0.5 gpm/sq ft. The fires could be reignited after extinguishment, but they burned less intensely. The probable mechanisms of extinguishment are dilution, blanketing, and inhibition by halogens. Since trichlorotrifluoroethane boils at 115.7°F, well above the fire point of 34°F for UDMH, cooling by evaporation of the agent does not appear to be a mechanism of extinguishment. Although dense white fumes were given off when the trichlorotrifluoroethane contacted the burning UDMH, there was no increased intensity of the fire such as the one caused when chlorobromomethane was added to hydrazine. Trichlorotrifluoroethane might be useful under conditions of limited access to the fire. The rapid extinguishment times and smaller amounts of agent required make the trichlorotrifluoroethane a more effective agent than water sprays or foam, but, of course, much less generally available. However on the basis of the weight of agent required for extinguishment, sodium bicarbonate was almost 4 times as effective.

e. Foam

A 6-per cent alcohol foam,** was an effective extinguishing agent for UDMH fires even though UDMH broke down the foam more rapidly than hydrazine.

Results of experiments with 6.5- and 49-sq in fires are shown in Figure 26. The average concentrations of 35 to 55 per cent of UDMH remaining after extinguishment are well above the minimum concentrations that support combustion. Because the foam in effect is a gentle application of water, the foam initially decomposes to release water, which then mixes with and dilutes the UDMH. Extinguishment then requires more foam at the surface.

This dilution mechanism is similar to that for hydrazine. UDMH, requires more water, however, because of mixing and concentration gradients.

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* Freon 113.

** For extinguishment of alcohol fires.

TABLE IX

Extinguishment of UDMH Fires
by Trichlorotrifluoroethane

Liquid Depth (inch)	Extinguishment Time (seconds)	Normalized Extinguishment Agent Required (gal Freon/gal UDMH)
0.093	6.9	0.99
0.186	6.7	0.48
0.279	9.5	0.45
0.372	24.0	0.66

NOTE:

(1) UDMH temperature 80°F.

(2) Trichlorotrifluoroethane temperature 80°F.

(3) Preburn time 10 seconds.

(4) Fire size 6.5 sq in.

(5) Application rate 0.5 gpm/sq ft = 0.1 lb/sec per sq ft.

(6) Extinguishment times are average of two tests.

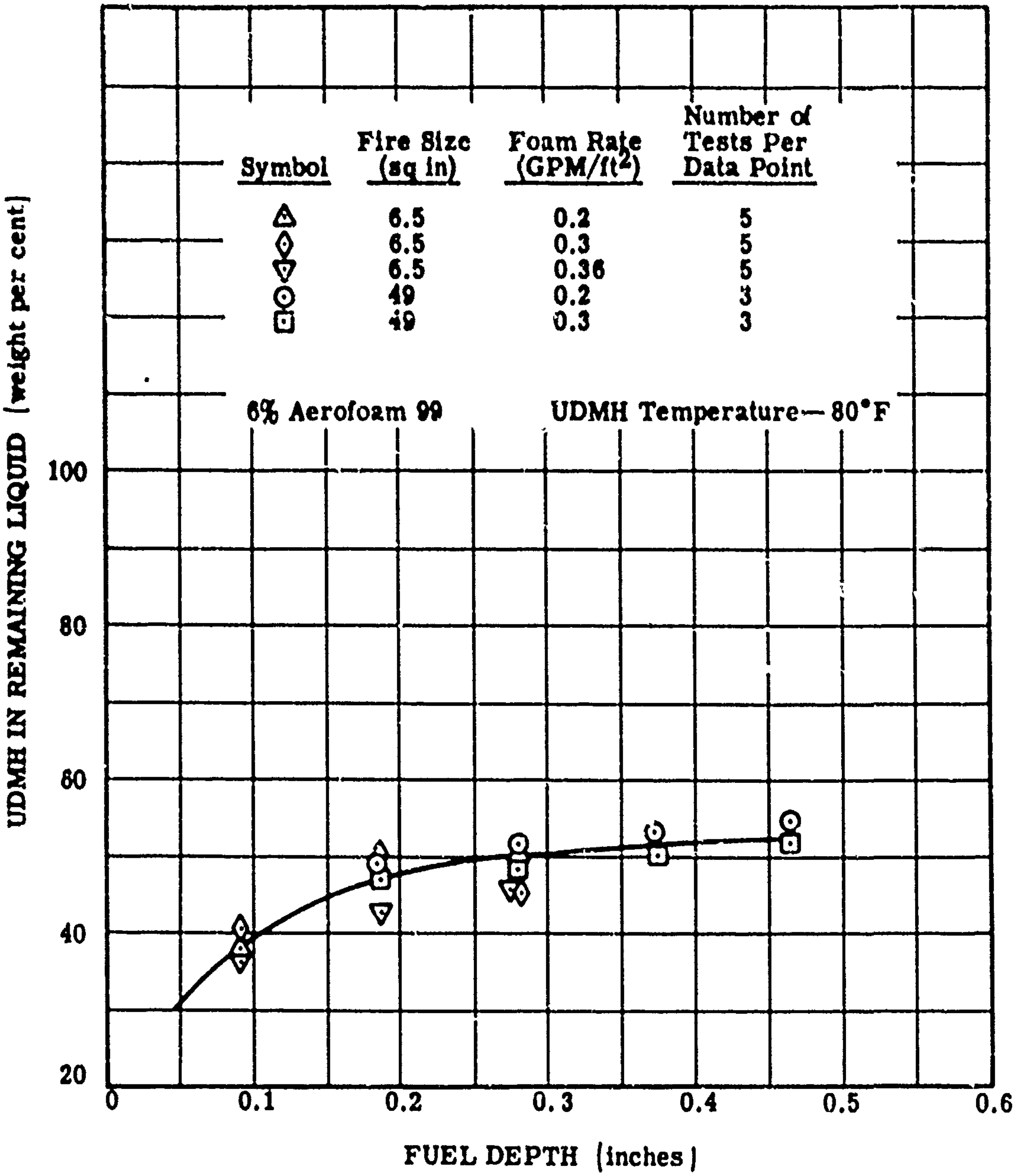

Figure 26. EXTINGUISHMENT OF UDMH FIRES BY FOAM—
FINAL UDMH CONCENTRATION VERSUS FUEL DEPTH

Figure 27 shows that the relative amounts of liquid in the foam required for extinguishment decreased with increased fuel depth. This observation is attributed directly to the concentration gradients discussed above. Increasing the pan diameter did not increase the amount of foam required per gallon of fuel at constant depth.

Although the exact relationship has not been established, the effectiveness of foam is increased by faster application rates. Therefore, scaling factors would be function of fuel depth, fuel volume, and rate of application of foam.

4. Summary of UDMH Fires Extinguishment and Comparison with Other Fuels

a. Water

Water applied rapidly as a forceful, coarse spray, and directed toward the base of the flame, is recommended. A minimum total amount of 2.5 gal of water (distributed uniformly) per gal of fuel is required to insure extinguishment. The minimum requirement of 2.5 gal per gal of fuel is about 25 per cent more than the minimum requirement for the 50:50 mixture, and about 250 per cent of the requirement for hydrazine.

b. Dry Chemical

Dry chemicals extinguished UDMH fires more rapidly than any other agent. About 0.1 lb/sq ft is required. Extinguished fires can reignite, however, by either a hot source or N_2O_4 vapors. Water is recommended as an auxiliary agent applied after extinguishment to eliminate this hazard.

The minimum requirement of 0.1 lb/sq ft is equivalent to that for JP-X and 50:50 mixture fires, but 2.5 times greater than that for hydrazine fires.

c. Foam

Foam effectively extinguished UDMH fires when 0.25 gal of contained liquid per sq ft of fire was applied. For fuel depths greater than 0.16 inch, less water is required in a foam than in a water spray.

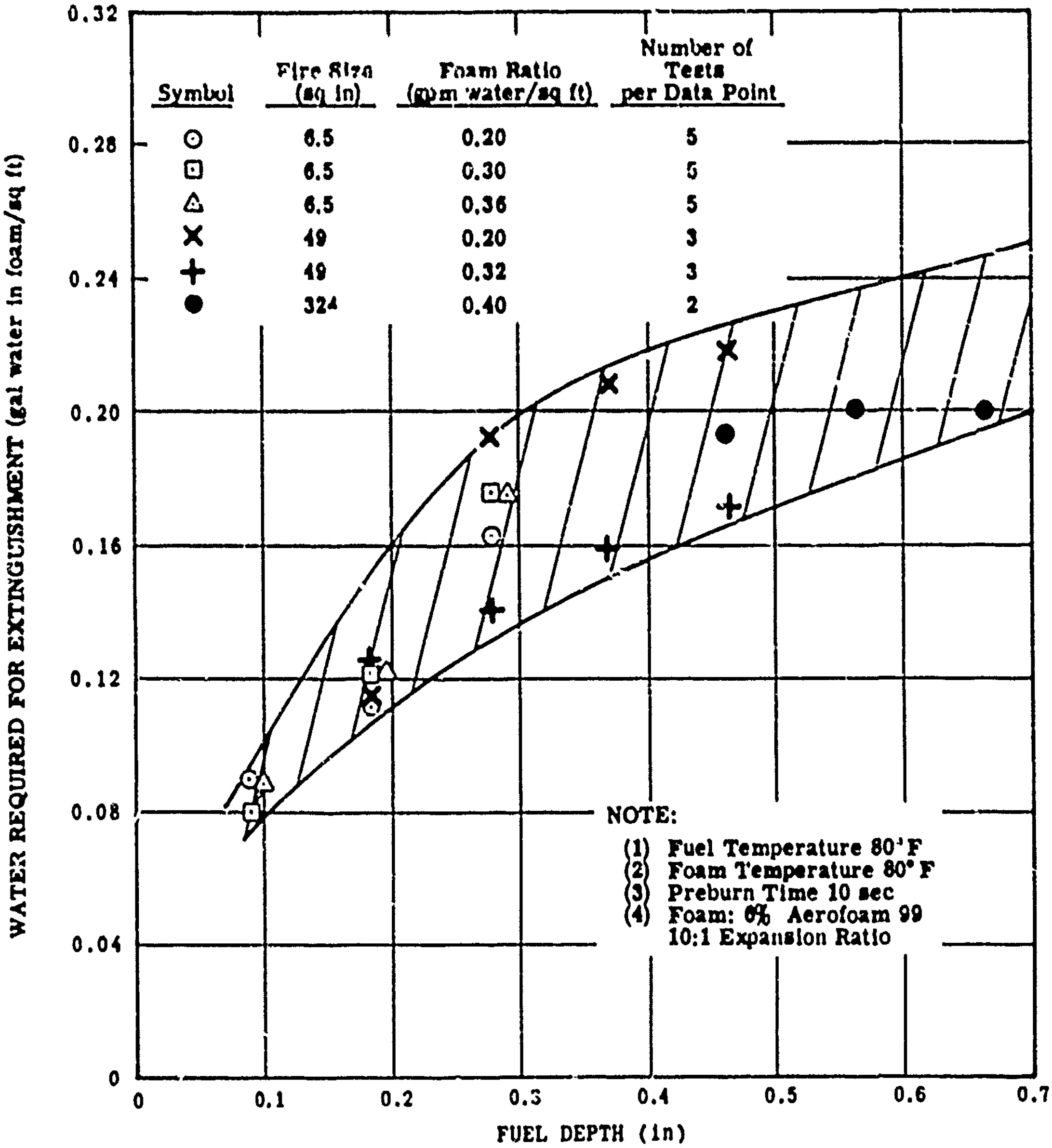

Figure 27. THE EFFECT OF FUEL DEPTH ON AMOUNT OF FOAM REQUIRED TO EXTINGUISH UDMH FIRES

However, because water spray can be more easily applied, it will probably be more desirable unless very deep pools of fuel are involved or, because of a limited supply, water must be used most efficiently.

The minimum requirement of 0.25 gal/sq ft is about 250 per cent of the minimum requirement of 0.1 gal/sq ft of hydrazine and about 50 per cent greater than the requirement of 0.15 gal/sq ft for JP-X or 50:50 mixture fires.

Either water, dry chemical or foam will require 2.5 times as much agent for fighting UDMH fires as for fighting hydrazine fires.

d. Other Agents

Trichlorotrifluoroethane was found more effective than water, but less effective than sodium bicarbonate. Although trichlorotrifluoroethane requires 1.0 gal per gal of UDMH and water requires 2.5 times as much, water is recommended preferentially because of general availability and lower cost.

5. JP-X Fires

JP-X is a blend of JP-4 hydrocarbon fuel (60 weight per cent) and UDMH (40 weight per cent). It has the appearance of JP-4 and the odor of UDMH. When water is added to JP-X, UDMH separates from the hydrocarbon into the water layer. Table X shows that if eight volume per cent water is added to JP-X, 72 per cent of the UDMH separates. Thus, when water is added to a JP-X fire, the water and UDMH forms the bottom layer and the upper layer is mostly JP-4. The fire is then similar to a conventional hydrocarbon fire as long as the temperature of the underlying UDMH remains below its boiling point.

a. Water Spray

JP-X fires extinguished with water resulted in the formation of two immiscible layers. The UDMH-water layer settled to the bottom, and the fires continued burning until the upper layer of hydrocarbon was exhausted.

Results for the JP-X fires extinguished by forced vertical water spray are shown in Figures 28 and 29. Extinguishment time was a function

TABLE X

Miscibility of JP-X and Water

Amount of Water Added to JP-X (volume per cent)	Hydrocarbon Layer (volume per cent)	Water Layer (volume per cent)	UDMH Separated (volume per cent)
0	100	0	0
4	75	25	55
8	66	34	72
12	63	37	74

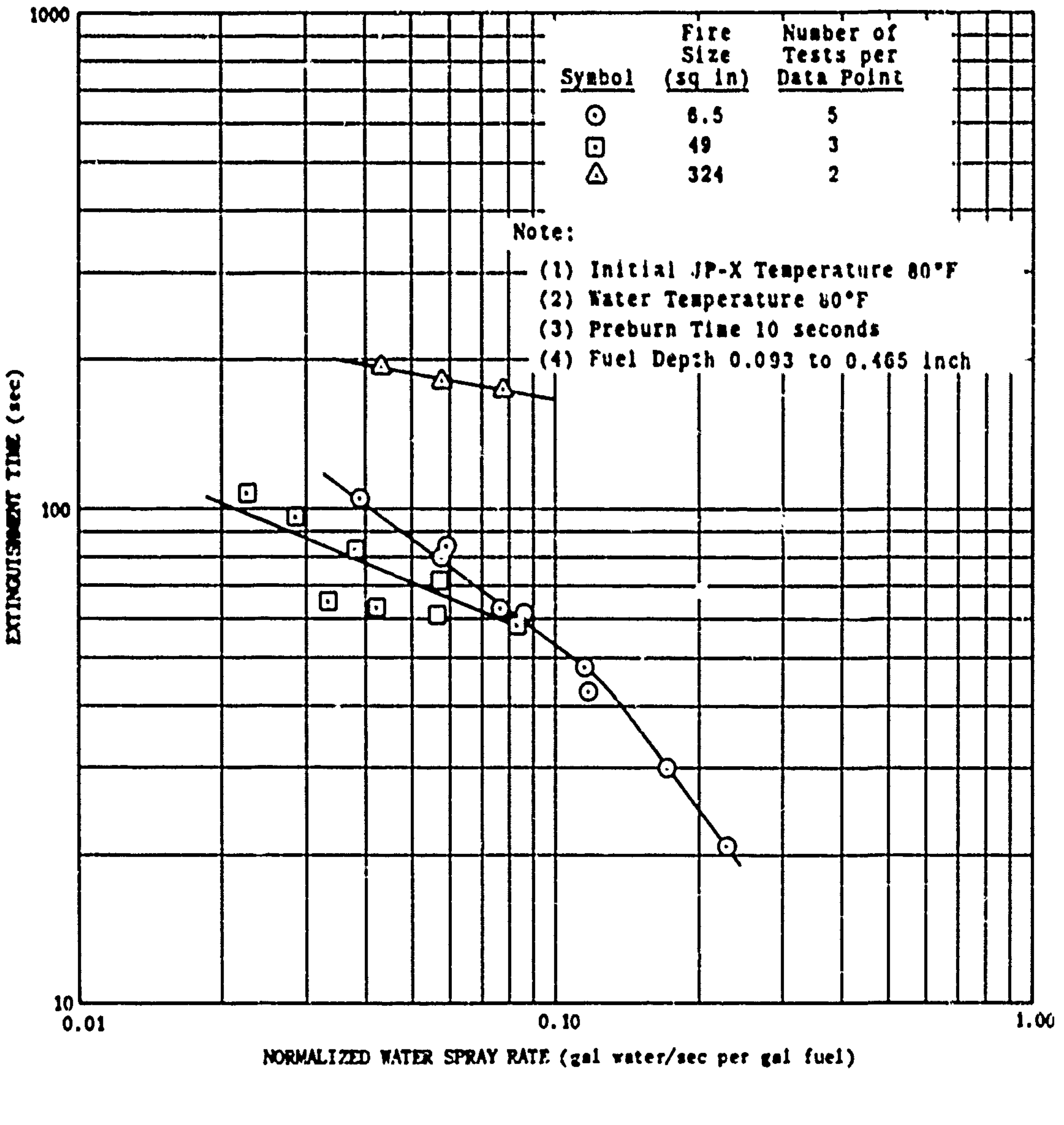

Figure 28. EFFECT OF NORMALIZED WATER SPRAY RATE ON EXTINGUISHMENT TIME OF JP-X FIRES

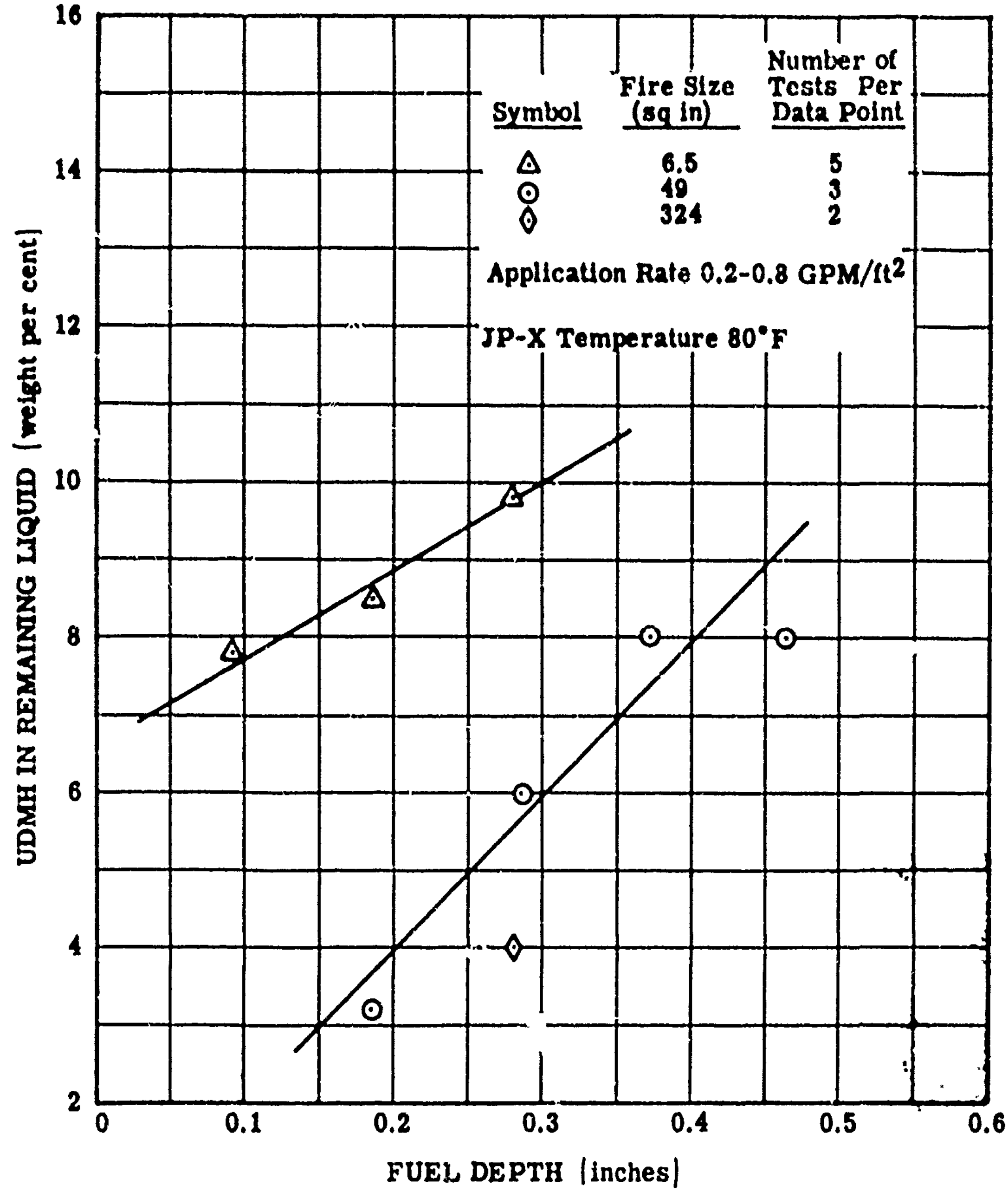

Figure 29. EXTINGUISHMENT OF JP-X FIRES BY WATER SPRAY—FINAL UDMH CONCENTRATION VERSUS FUEL DEPTH

of the normalized water spray rate. Since initial concentration of UDMH was 40 per cent, and all of the water ended up in the UDMH-water layer, the final concentration of UDMH in this layer was less than 10 per cent.

Larger fires in 324-sq in pans required much more water for extinguishment. Water spray intensified the flame, probably by forcing air into it.

It is concluded that water sprays are ineffective against this hydrocarbon-based fuel.

b. Dry Chemical

Sodium bicarbonate dry chemical powder was effective in extinguishing all sizes of JP-X fires investigated, as shown in Table XI.

TABLE XI

Extinguishment of JP-X Fires with Dry Powder

Fire Area (sq in)	Application Rate (lb/sq ft-sec)	Time for Extinguishment (sec)
6.5[a]	0.055	< 2
49	0.0083	< 2
324	0.016	< 5

a. Application of 0.0194 lb/sq ft per sec by aspirator bulb extinguished one of three fires and 0.0242 lb/sq ft per sec extinguished all three fires.

The dry powders are the most effective agent against the hydrocarbon-hydrazine types of fires where rapid extinguishment with a minimum of agent is important. However, the fuel can be reignited.

c. Foam

UDMH in the JP-X fuel breaks down the alcohol-type foam. The UDMH quickly separates to the bottom as a water-miscible layer. Fresh

foam then blankets and extinguishes the burning concentrated hydrocarbon in the upper layer.

Foam extinguishment of JP-X fires was evaluated in 6.5-, 49-, and 324-sq in burners. Results are summarized in Figure 30. Foam was almost equally effective against 49- and 324-sq in fires. Both of these larger fires required less foam than the 6.5-sq in fires. Although the JP-X fires required approximately 50 per cent more foam per unit area than pure UDMH did in the 6.5-sq in pan, the 49- and 324-sq in fires required about one-third less. The reason for this is not known.

6. Summary of JP-X Fires Extinguishment and Comparison with other Fuels

a. Water

Water spray was ineffective against JP-X fires, especially in large fires, where the hydrocarbon fraction was consumed. The remaining UDMH could then be extinguished by dilution with water. In some small fires, JP-X was rapidly extinguished by water. This is attributed to blanketing and cooling effects by the impinging spray; in large fires, these effects were not significant enough to extinguish the flames.

b. Dry Chemical

Dry chemicals extinguished JP-X fires more rapidly than any other agent. About 0.1 lb/sq ft was required. Extinguished fires can reignite, however, by either a hot source or N_2O_4 vapors. Water is recommended as an auxiliary agent applied after extinguishment to eliminate this hazard.

Dry chemicals were equally effective against UDMH, JP-X, and 50:50 mixture fires. Hydrazine fires, however, required 75 per cent less dry powder per unit area for extinguishment.

c. Foam

Foam effectively extinguished JP-X fires when 0.16 gal of contained liquid per sq ft of fire was applied. This is the only method in which water can be utilized as an extinguishing agent for this type of

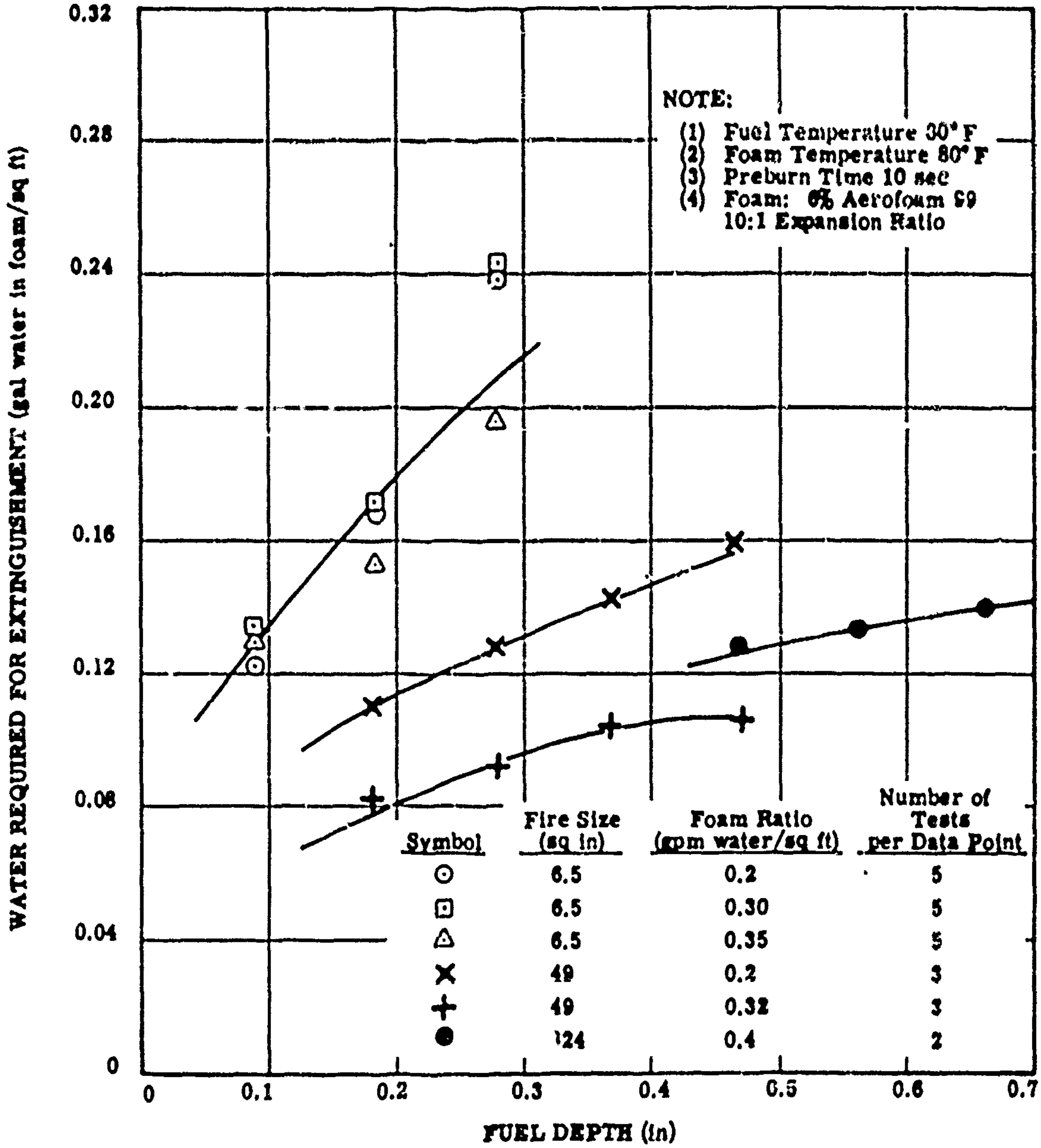

Figure 30. THE EFFECT OF FUEL DEPTH ON AMOUNT OF FOAM REQUIRED TO EXTINGUISH JP-X FIRES

fire. The hydrocarbon is extinguished by the combined effects of blanketing and cooling. UDMH is extinguished by these and dilution. The principal factors that determine the amount of agent are fuel depth and fuel area.

The minimum requirement of 0.16 gal per sq ft of JP-X is intermediate between the 0.1 gal/sq ft required for hydrazine and the 0.25 gal/sq ft required for UDMH fires. It is nearly equal to the 0.15 gal/sq ft required against fires of the 50:50 mixture.

7. 50:50 UDMH:Hydrazine Fires

The extinguishment of fires involving the 50:50 mixture by weight of hydrazine and UDMH is of particular interest since this combination has been selected as the fuel for the Titan II missile system.

Although the mixture contains only 35 mol per cent UDMH, investigators have found that the vapors above the mixture are primarily UDMH and that the initial boiling point of the mixture is between 149 and 160°F.[2,12] The boiling point of pure UDMH is 146°F. These investigators have also found that the UDMH is easily distilled from the mixture and leaves a residue of essentially pure hydrazine. A fire involving the mixture would therefore closely resemble a UDMH fire during the initial stages, and a hydrazine fire during the final stages. Since the density of the mixture, 0.9 gm/ml, is less than the density of water, the mixture will behave similarly to UDMH when water is applied.

a. Water Spray

The time required for water sprays to extinguish fires of the 50:50 mixture in the 6.5-sq in burner is shown in Figure 31 as a function of the normalized spray rate. Similar data for UDMH are included for comparison. Fires involving the mixture required approximately the same application time of spray before extinguishment, and hence the same amount of water as UDMH. Differences between the two curves at very high rates are slight and may be within the limits of experimental error.

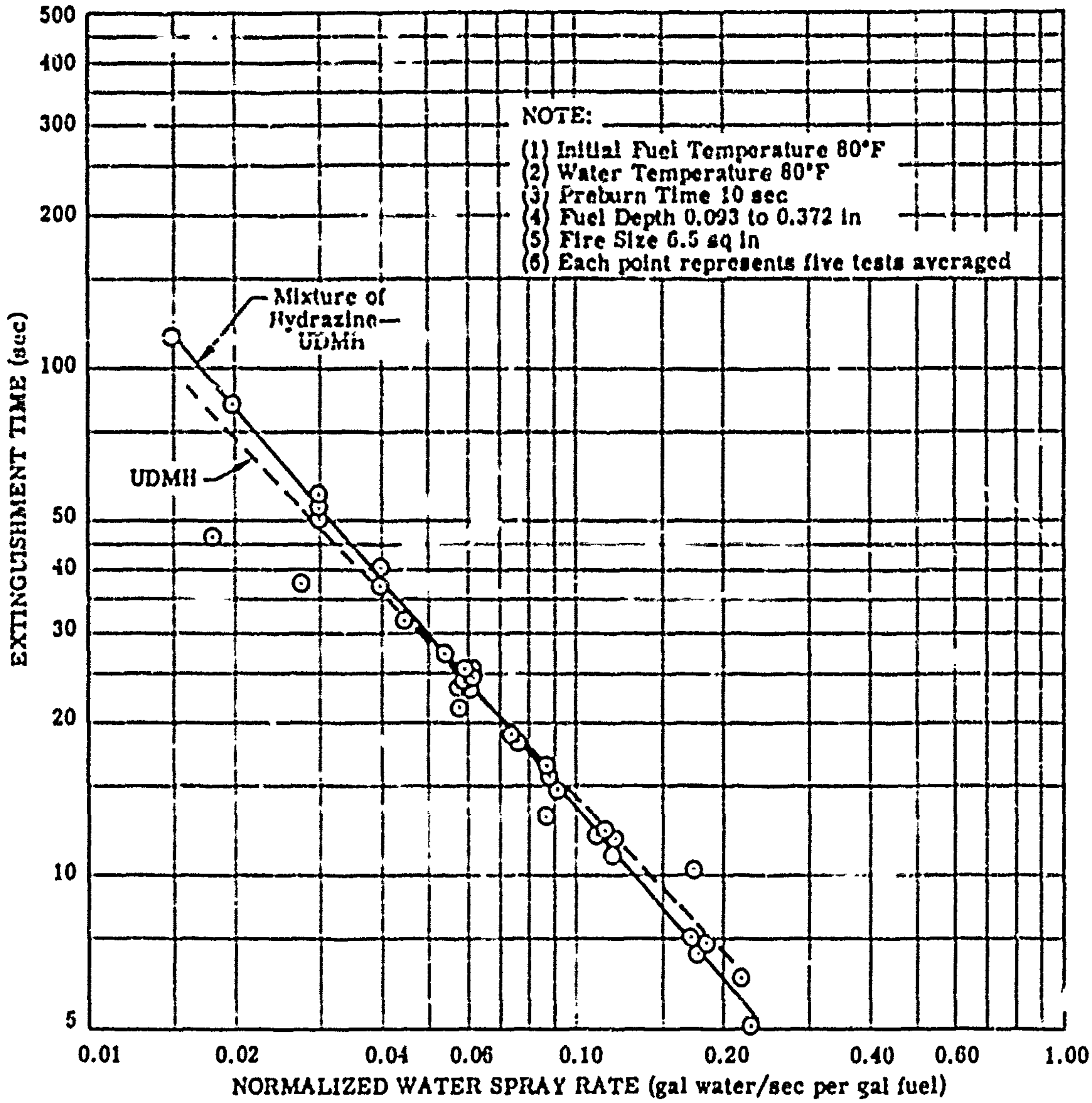

Figure 31. EFFECT OF NORMALIZED WATER SPRAY RATE ON EXTINGUISHMENT TIME OF FIRES INVOLVING A 50:50 MIXTURE OF HYDRAZINE AND UDMH IN 6.5-sq in PAN

Additional data for the time required for water sprays to extinguish fires involving a 50:50 mixture of hydrazine and UDMH are shown in Figure 32 as a function of the normalized spray rate. The fact that the data correlate on this type of plot confirms previous results that dilution is the major mechanism of extinguishment.

For the four pan sizes investigated, the number of gallons of water required for extinguishment was roughly proportional to the number of gallons of fuel spilled. There appeared to be a trend toward increasing extinguishment times (more water required per gallon of fuel) with increasing pan size. However, the results for the 6.5-sq in pan indicate that fires required more time for extinguishment at low normalized water spray rates than would be expected from the rest of the data. This may be because of heat-transfer effects at the pan edges which become important in the smallest size pan.

The percentage of fuel remaining after extinguishment in various pan sizes were investigated. The analytical technique was that recommended by Edwards Air Force Base[11] for hydrazine-UDMH mixtures. Results are shown in Figure 33, as a function of normalized spray rate. The wide scatter resulted from errors in the analyses and from the inherent variability of the fires. The errors are magnified in the percentage data. The postulate that the UDMH in the mixture burns first is confirmed by the fact that at low spray rates only 30 to 60 per cent of the UDMH remained unburned, whereas 80 per cent of the hydrazine remained.

The effect of fire size on the percentage of fuel consumed is difficult to determine. However, it appears that less fuel was consumed as the fire size increased.

It is concluded that water sprays are effective against fires involving the 50:50 mixture of hydrazine and UDMH The amount of water required (approximately 2.0 gal of water per gal of fuel) is about 80 per cent of that required to extinguish fires involving pure UDMH.

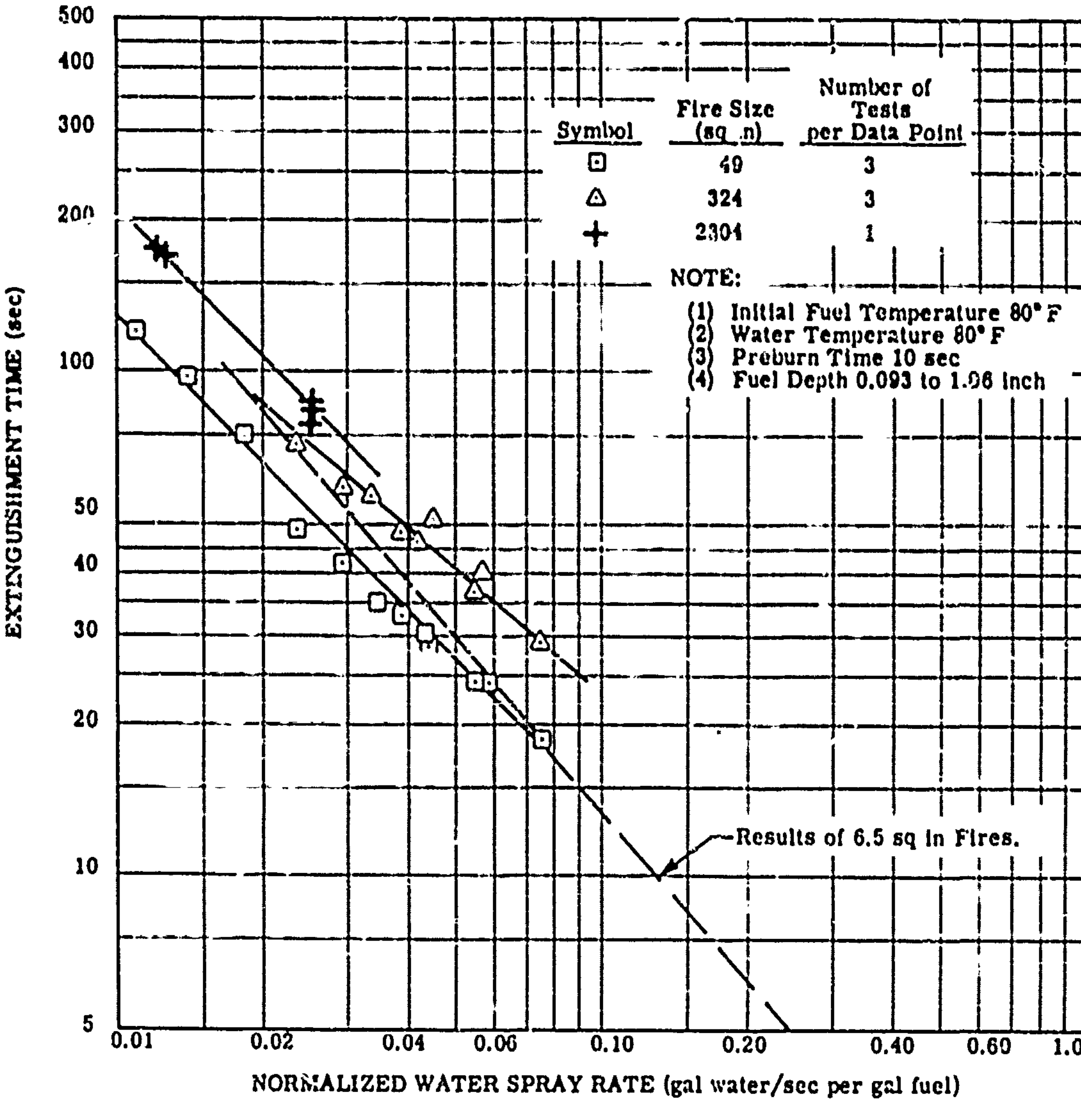

Figure 32. THE EFFECT OF NORMALIZED WATER SPRAY RATE ON EXTINGUISHMENT TIME OF FIRES INVOLVING A 50:50 MIXTURE OF HYDRAZINE AND UDMH

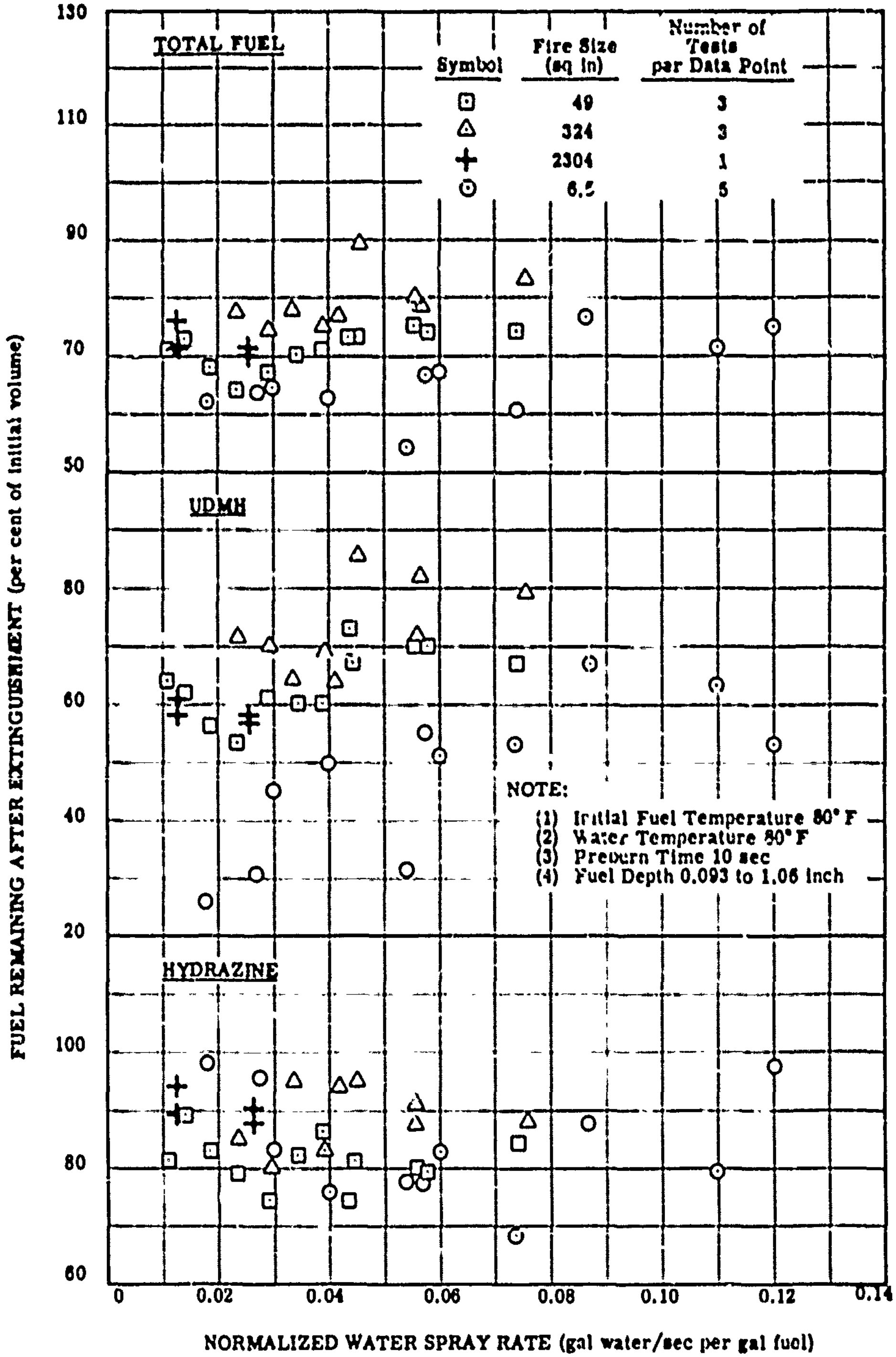

Figure 33. WATER SPRAY RATE ON THE AMOUNT OF 50:50 MIXTURE REMAINING AFTER EXTINGUISHMENT

b. Dry Chemical Agents

Sodium bicarbonate powder effectively extinguished fires in the 49-, 324-, and 2304-sq in pans when applied at a rate of 0.0133 lb/sec per sq ft. The fires in the 49-sq in pan were extinguished almost immediately; those in the 324-sq in pan in 3 to 8 seconds; and those in the 2304-sq in pan in 6 to 9 seconds. As little as 0.024 lb/sq ft of powder extinguished the fires in the 6.5-sq in burner in less than 1 second.

The increased difficulty of evenly distributing powder in the larger pans accounts for the increased extinguishment time. The dry chemical agent was applied from a fixed nozzle located above the smaller fires. A 2.5 lb hand extinguisher was used to extinguish the 2304-sq in fire which required "sweeping' the surface to completely cover and extinguish the fire.

Because of the rapidity of extinguishment, dry chemical agents are very useful in extinguishing fires involving the 50:50 mixture. However, the fires could be reignited by a hot wire. Therefore, dry chemicals should be used in conjunction with water dilution if ignition sources persist.

c. Vaporizable Liquid Agents

Bromotrifluoromethane* when applied at a rate of 0.04 lb/sec per sq ft, failed to extinguish fires involving the 50:50 mixture in the 6.5-sq in burner. The agent was applied in gaseous form and directed on the fire both from above and from the side. It did not react with the burning fuel.

It is concluded that bromotrifluoromethane should not be relied upon as an extinguishing agent for fires involving the 50:50 mixture.

d. Carbon Dioxide

Gaseous carbon dioxide applied at a rate of 0.17 lb-sq ft/sec failed to extinguish fires involving the 50:50 mixture in the 6.5-sq in burner. No attempt was made to direct the carbon dioxide 'snow' that formed on the fire. The flames changed from yellow to blue; this indicates combustion of carbon monoxide. This value of 0.17 lb-sq ft/sec is greater than the NFPA recommendation of 0.04 lb-sq ft/sec for general fire extinguishment.

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* Freon 13B1

e. Foam

An alcohol-type foam was slightly more effective against the 6.5- and 49-sq in fires of the 50:50 mixture than fires of pure UDMH. Much less foam was required to extinguish the fires in the 324-sq in pan. On the basis of the amount of water required, the foam was more effective than water spray in extinguishing fires of the mixture.

The amount of water contained in the foam as a function of fuel depth is shown in Figure 34. These data show that for the smaller pans the amount of foam required per unit area increased with fuel depth. The amount of foam required for the larger fires, which coincidentally are the deeper pools, do not indicate this dependance. Comparison of Figures 34 and 27 confirms the increased effectiveness of foam against fires of the mixture over pure UDMH.

The 324- and 2304-sq in fires required less foam per unit area than did the smaller fires. This result is not fully explained by increased extinguishment efficiency at higher application rates.

The amount of unburned fuel after extinguishment as a function of initial fuel depth is shown in Figure 35. The fraction of fuel burned decreased with increased depth. Also, less hydrazine than UDMH was consumed in the fire, due to the higher vapor pressure of UDMH.

A series of tests was made to determine the effectiveness of ordinary mechanical foams against fires involving the 50:50 mixture. As seen from Figure 36, the amount of ordinary foam required is much more than the amount of alcohol-type foam, and almost as great as the amount of water spray. The ordinary foam broke down much faster than did the alcohol type and did not stabilize until the fire was almost extinguished by dilution. The alcohol-type foam should therefore be used instead of the ordinary foam concentrate.

8. Summary of 50:50 UDMH-hydrazine Fires extinguishment and Comparison With Other Fuels

a. Water

Water applied rapidly as a forceful, coarse spray, and directed toward the base of the flame, is recommended. A minimum total amount of

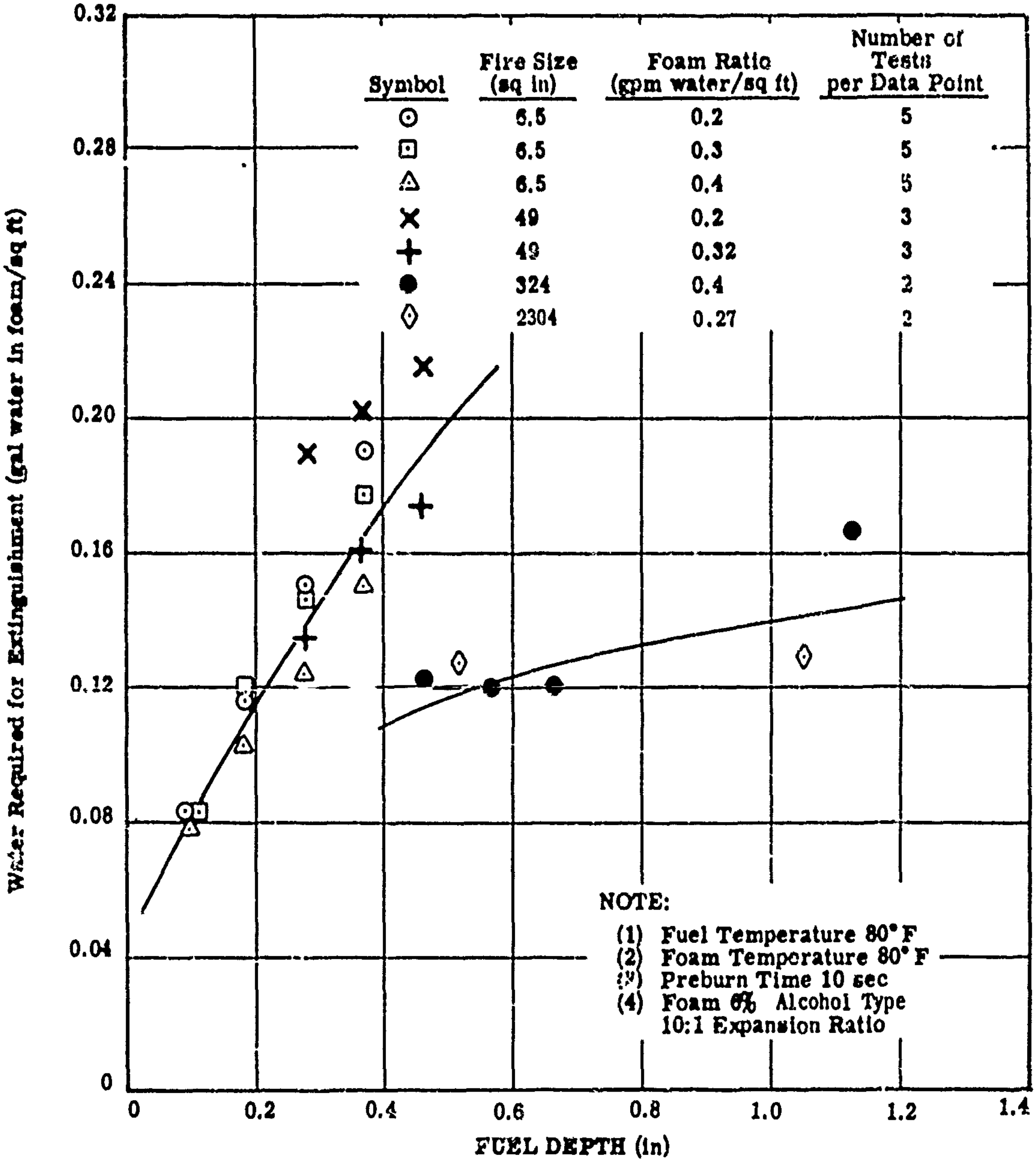


Figure 34. THE EFFECT OF FUEL DEPTH ON AMOUNT OF FOAM REQUIRED TO EXTINGUISH 50:50 MIXTURE FIRES

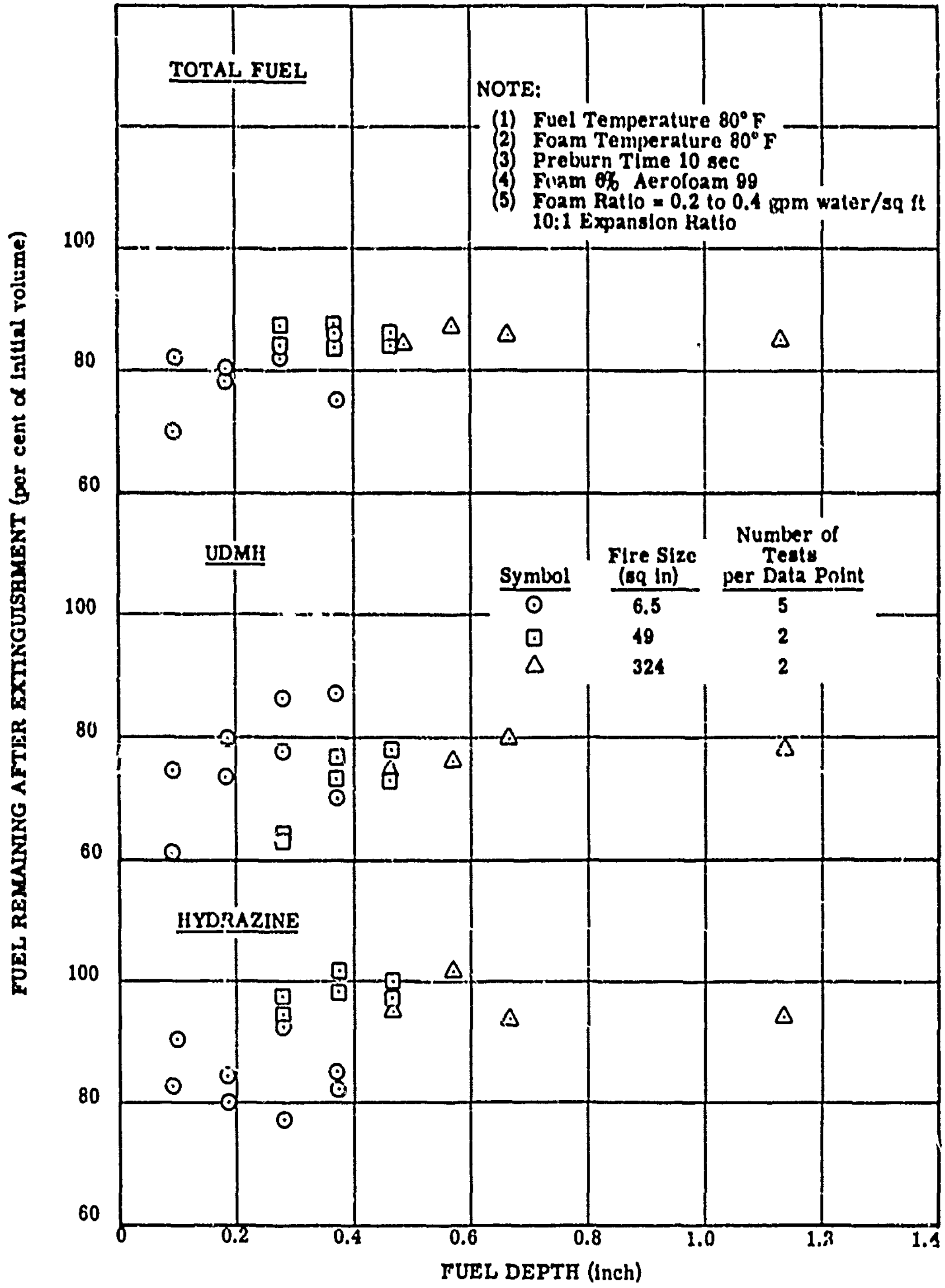


Figure 35. EFFECT OF FUEL DEPTH ON AMOUNT OF 50:50 MIXTURE REMAINING AFTER EXTINGUISHMENT BY FOAM

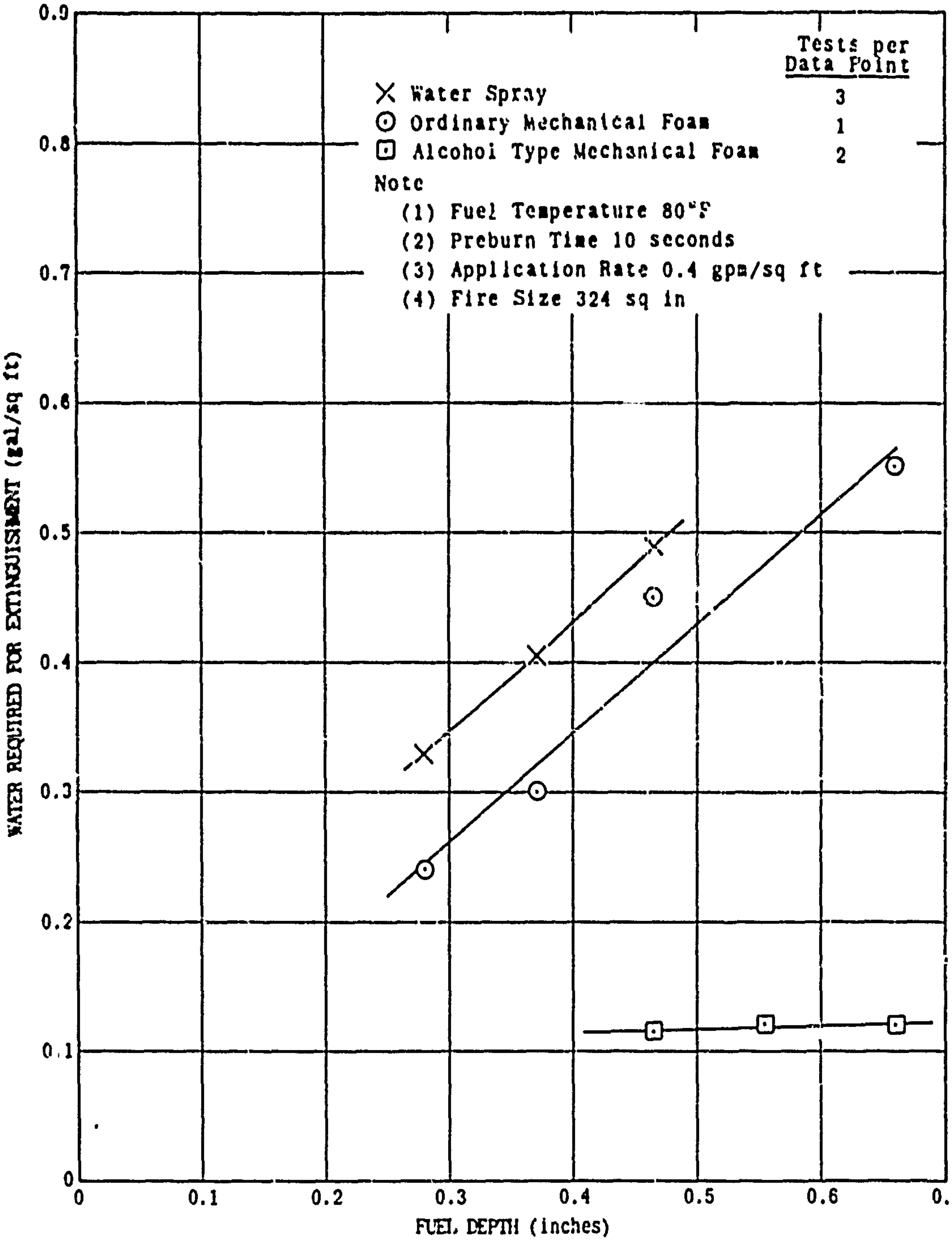


Figure 36. COMPARISON OF FOAMS AND WATER SPRAYS FOR EXTINGUISHING FIRES OF 50:50 MIXTURE

2.0 gal of water (distributed uniformly) per gal of fuel is required to insure extinguishment. This requirement is twice that for hydrazine fires and 20 per cent less than that for pure UDMH fires. Therefore, fires of the mixture exhibit a net behavior closer to UDMH than to hydrazine fires. This conclusion also follows from the assumption that the more volatile UDMH burns during early stages of the fire since these stages have the greatest influence on extinguishment parameters.

b. Dry Chemical

Dry chemicals extinguished 50:50 mixture fires more rapidly than any other agent. About 0.1 lb/sq ft is required. Extinguished fires can reignite, however, by either a hot source or N_2O_4 vapors. Water is recommended as an auxiliary agent applied after extinguishment to eliminate this hazard.

The minimum requirement of 0.1 lb/sq ft is equivalent to that of pure UDMH or JP-X fires, but 2.5 times greater than that for hydrazine fires. This further illustrates the similar behavior of the pure UDMH and the 50:50 mixture.

c. Foam

Foam effectively extinguished 50:50 mixture fires when 0.15 gal of contained water per sq ft of fire was applied. For fuel depths greater than 0.12 inch, less water is required in a foam than in a water spray. However, because water spray can be more easily applied, it will probably be more desirable unless very deep pools of fuel are involved, or because of a limited supply, water must be used most efficiently.

The requirement of 0.15 gal per sq ft of 50:50 mixture, although equal to the requirement of JP-X, lies between the values of 0.1 gal/sq ft for pure hydrazine and of 0.25 gal/sq ft for pure UDMH.

d. Other Agents

Neither bromotrifluoromethane nor carbon dioxide were effective extinguishing agents for fires of the 50:50 mixture. These agents are not recommended.

9. Extinguishment Tests in a Silo Configuration

The effectiveness of the various agents against fires in a silo configuration was determined by tests in the 1/50-scaled Titan II silo. The quantity of fuel used in these tests (115 ml) corresponded to a spill of about 25 per cent of the missile contents. The resulting pool in the bottom of the silo was 6.2 inches in diameter with a maximum depth of 0.465 inch.

The height of the spray nozzle above the burning fuel determined the effectiveness of water spray applied at a rate of 0.8 gpm/sq ft (0.091 gal of water/sec per gal of fuel). Thus when the nozzle was placed one foot above the burning liquid most of the spray impinged on the liquid with the result that the fire extinguished in 2 or 3 seconds. When the nozzle height was increased to 3 ft above the burning surface, most of the water impinged on the sides of the silo and drained down into the fuel with the result that the time required to extinguish the fire increased to 32 seconds. Fires involving the same depth of fuel in the 49-sq in pan were extinguished in 29 seconds when water spray was applied at the same rate of 0.8 gpm/sq ft.

Evidently, two different mechanisms were involved in the extinguishment. When the nozzle was located one foot above the burning surface extinguishment was probably by blanketing or smothering actions which excluded oxygen from the flame. When the nozzle was raised to 3 ft above the fire, extinguishment was caused by dilution of the fuel. The effectiveness of water sprays in a silo configuration will therefore be determined by the location of the nozzles relative to the burning liquid.

The technique for applying foam also influenced the effectiveness of this agent against fires in the model silo. When the foam was dropped into the burning fuel (at a rate of 0.4 gpm/sq ft) from a height of 3 ft, the fires extinguished when 0.170 gal of contained liquid per sq ft of fuel was added. When the foam was allowed to flow down the walls of the silo, less mixing occurred and the fires extinguished when 0.117 gal of contained

liquid per sq ft of fuel was added. Foam applied at a rate of 0.32 gpm/sq ft to fires in the 49-sq in pan extinguished the fires after 0.170 gal of contained liquid/sq ft had been added. These tests confirm the effectiveness of foam and indicate that a gentle application of foam is more effective than an application which promotes mixing.

A sodium bicarbonate dry chemical powder applied at a rate of 0.0085 lb/sq ft per sec (0.00061 lb/cu ft per sec) extinguished the silo fires immediately.

The above tests indicate that the results of the open pan extinguishment tests can be applied to fires in a silo configuration. The effectiveness of water sprays can be improved considerably if the spray nozzles can be located close to the burning liquid. However, if the sprays cannot exclude oxygen from the flame, then the same amount of water will be required for silo and for open pan fires. Sodium bicarbonate dry chemical powders extinguished fires most rapidly in either the silo or open pans.

10. Fires Oxidized by Nitrogen Tetroxide

a. Nitrogen Tetroxide Vapors

All the hydrazine-type fuels (hydrazine, UDMH and mixtures) ignited hypergolically when a jet of nitrogen tetroxide vapor was directed onto their surfaces. The lowest concentrations of water-diluted fuels which ignited hypergolically or burned in nitrogen tetroxide vapors are shown in Table XII.

Nitrogen tetroxide vapors provided a ready source of ignition at hydrazine concentrations above 60 weight per cent at ambient temperatures, UDMH concentrations above 65 weight per cent, and the 50:50 mixture concentrations above 55 weight per cent. Once ignited, the fuels burned at even lower concentrations in nitrogen tetroxide vapors. In the event of spills which contact nitrogen tetroxide vapors, almost equal amounts of water will be required to prevent ignition and larger amounts will be required to extinguish fires.

Test results for extinguishing the 50:50 mixture fires (with nitrogen tetroxide vapors) by water sprays are shown in Figure 37. Fires oxidized

TABLE XII

Hypergolic Ignition or Combustion of Hydrazine-Type Fuels With Nitrogen Tetroxide Vapors

Fuel	Fuel Temperature (°F)	Minimum Fuel Concentration in water (weight per cent) For Hypergolic Ignition	For Combustion
Hydrazine	80	60	60
Hydrazine	140	55	45
Hydrazine	205		35
UDMH	80	65	30
50:50 Mixture	80	55	45
50:50 Mixture	140	50	

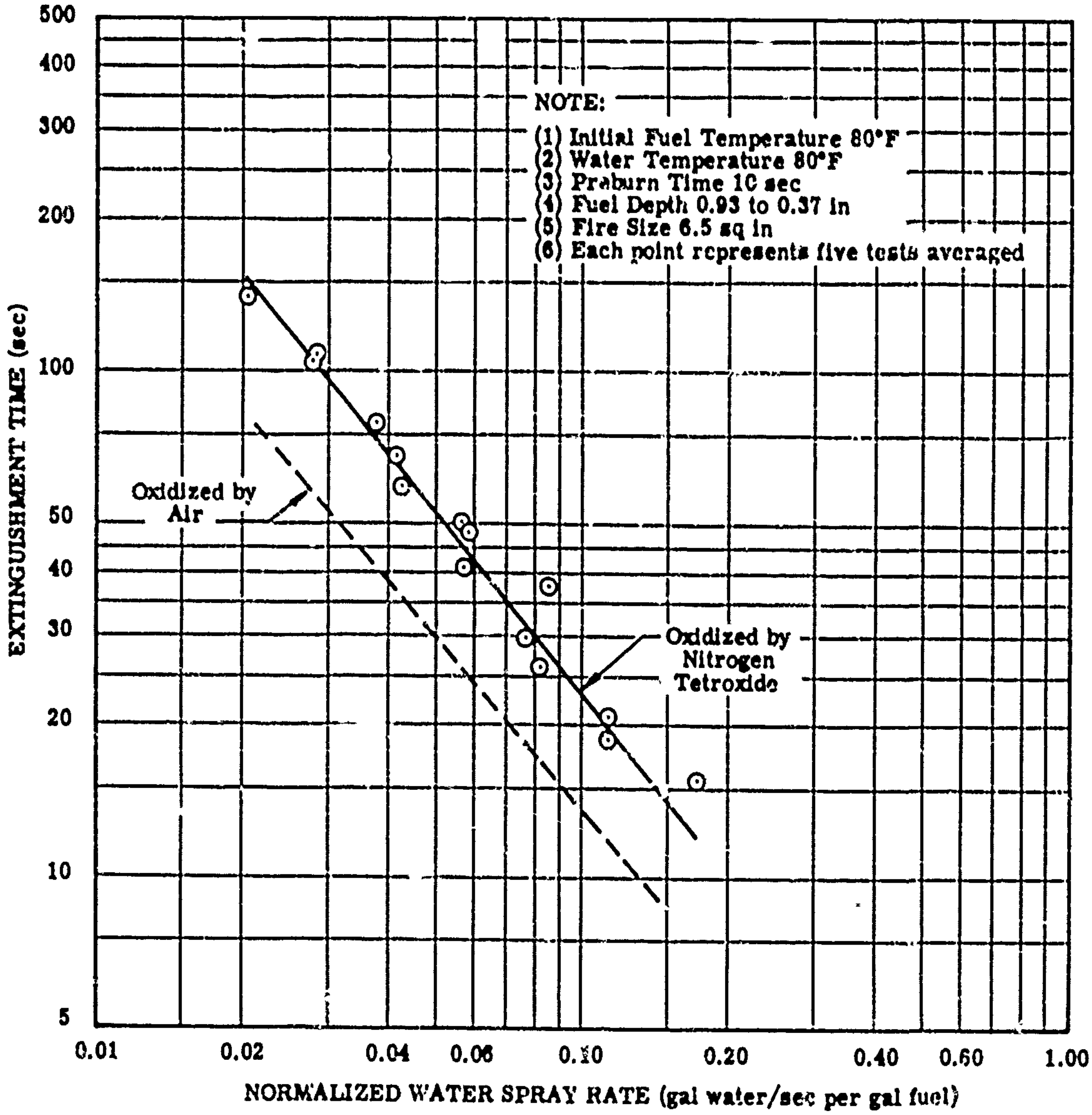


Figure 37. EFFECT OF NORMALIZED SPRAY RATE ON EXTINGUISHMENT TIME OF A 50:50 MIXTURE OF HYDRAZINE AND UDMH OXIDIZIED BY NITROGEN TETROXIDE VAPORS

by air are shown for comparison. The time required for extinguishment of fires involving the 50:50 mixture and nitrogen tetroxide vapors was a function of the normalized water spray rate. This indicates that dilution is the chief mechanism of extinguishment. The time required to extinguish fires in nitrogen tetroxide vapors was almost twice that required in air at a given spray rate; consequently, twice as much water was required to dilute the fires in nitrogen tetroxide. This is confirmed by Figure 38 which also shows that at increased spray rates water was more effective.

When water spray was applied at a rate of 0.6 gpm/sq ft to pools of fuel 0.093-inch deep in the 6.5-sq in pan, the amount of water required for extinguishment of hydrazine, UDMH, and 50:50 mixture fires was 1.67, 3.8, and 2.7 gal of water per gal of fuel, respectively. These are twice the amounts required to extinguish air-oxidized fires under similar conditions.

It is concluded that the mechanism of extinguishment of nitrogen tetroxide-oxidized fires by water sprays is the same as that for air-oxidized fires, i.e., dilution. However, more than twice as much water is required because more dilute solutions of the fuels will support combustion in the presence of nitrogen tetroxide vapors.

b. Liquid Nitrogen Tetroxide

(1) Laboratory Results

Initial experiments with fires involving liquid nitrogen tetroxide were made using 10 ml each of hydrazine and nitrogen tetroxide. When these propellants were dumped simultaneously into the 6.5 sq in pan they burned vigorously for three seconds, threw white sparks of burning liquid into the flame, and finally exploded, severely damaging the laboratory hood and splitting the seams of the metal pan. Calculations showed that overpressures between 0.5 and 1 psi are sufficient to cause the damage to the laboratory hood. This overpressure is calculated for the instantaneous combustion of 10 ml of fuel with nitrogen tetroxide if the gases are confined in the 140-cu ft hood.

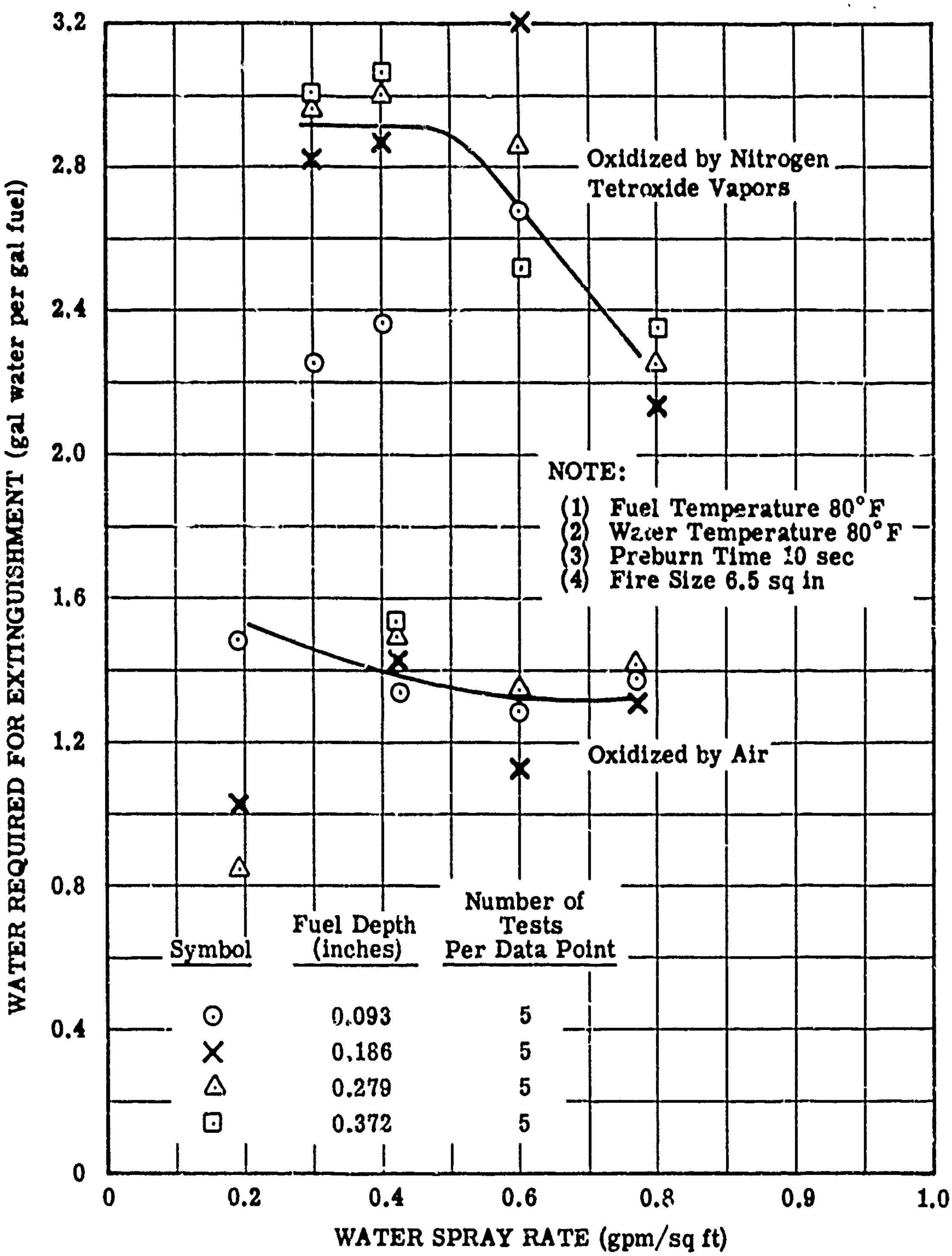


Figure 38. EFFECT OF WATER SPRAY RATE ON AMOUNT OF WATER REQUIRED TO EXTINGUISH 50:50 MIXTURE OF HYDRAZINE AND UDMH OXIDIZED BY AIR OR NITROGEN TETROXIDE VAPORS

Further experiments with the hypergolic reaction in the hood used only 3 ml of fuel and various amounts of oxidizer. Results of 97 tests are summarized in Table XIII. When sufficient quantities of fuel and oxidizer were present to assure intimate contact, there was a greater than 50 per cent probability of explosion. The order of addition did not appear to effect this probability.

When single drops of fuel were dropped from a height of 17 inches into a 0.180-inch-deep pool of nitrogen tetroxide, 31 of 32 samples exploded. The improved mixing of the higher velocity drops evidently increased the probability of explosion. The reports from these single drop explosions were as loud as those involving 3 ml of fuel and 10 ml of nitrogen tetroxide.

In general, the reports from the explosions involving pure hydrazine were louder than those involving the 50:50 mixture of hydrazine and UDMH. However, one explosion of 3 ml of the mixture was louder than any of the explosions involving 3 ml of hydrazine; two of the safety glass windows (1/4-inch-thick) of the hood cracked. The explosions of pure UDMH were less severe than those of either the mixture or pure hydrazine.

Non-exploding fires involving three ml of the 50:50 mixture burned for approximately 23 seconds. They were extinguished in four seconds by a water spray rate of 0.82 gpm/sq ft. Water spray did not explode the mixture in any of four experiments.

Ten ml of nitrogen tetroxide were spilled into three ml of the 50:50 mixture, which had been ignited and preburned for one second. Water spray at a rate of 0.82 gpm/sq ft extinguished the fire in eight seconds. One of four samples exploded before the water spray could be applied.

The effects of water as an impurity in the fuels were investigated. Hydrazine was dried over 5-A molecular sieves to reduce water from 3 per cent to less than 0.1 per cent. One of two samples exploded in contact with nitrogen tetroxide. Therefore water is not required for explosions. When 3 per cent of water was added to the 50:50 mixture to raise water content to 5 per cent explosions were more severe.

TABLE XIII

Summary of Experiments with Hypergolic Mixtures

FUEL	HYDRAZINE			UDMH			50:50 MIXTURE HYDRAZINE-UDMH		
Amount of Component and Method of Addition	Total Number of Tests	Number Exploded	Number Did Not Explode	Total Number of Tests	Number Exploded	Number Did Not Explode	Total Number of Tests	Number Exploded	Number Did Not Explode
10 ml both fuel and oxidizer dumped	1	1	0	0			0		
3 ml fuel dumped into 10 ml oxidizer	52	31[a]	21[a]	1	0	1	32[b]	15[b]	17
3 ml fuel dumped into 3 ml oxidizer	1	0	1	0			0		
5 ml oxidizer dumped into 3 ml fuel	4	4	0	0			1	1[c]	0
3 ml oxidizer dumped into 3 ml fuel	3	0	3	1	1	0	1	1	0
1 ml oxidizer dumped into 3 ml fuel	1	0	1	0			0		
1 drop fuel dumped into 20 ml of oxidizer from height of 17 inches	4	3	1	2	2	0	26	26	0
TOTAL	66	39	27	4	3	1	60	43	17

NOTE:
(1) Temperatures of components: nitrogen tetroxide = 70°F, Fuel = 80°F
(2) Hydrazine contained 3 per cent water unless otherwise noted
(3) Hydrazine-UDMH mixtures contained 2 per cent water unless otherwise noted
(4) UDMH contained 1 per cent water.

a. One of these contained < 0.1% water
b. Two of these contained 5% water
c. Contained 5% water

Addition of 5 weight per cent ethanol, isopropanol, or aniline to the mixture did not effect the frequency or severity of the explosions when single drops of 50:50 mixture were spilled into nitrogen tetroxide.

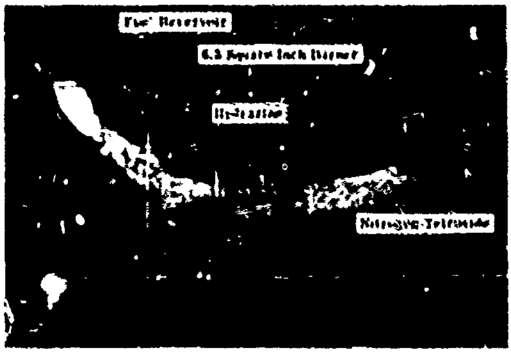
To determine the nature of the explosions the reaction between 3 ml of hydrazine and 10 ml of nitrogen tetroxide was photographed at 2750 frames per second. In one case, shown in Figure 39, the mixture exploded at or before contact of the two liquids. In another case, as shown in Figure 40, the sample exploded after the liquids had burned for 82 milliseconds.

(2) Large Scale 50:50 Mixture in Pans

To determine how larger quantities of fuel and oxidizer react, outdoor facilities were used for tests involving 3, 10, 30, 100, and 300 ml of the 50:50 mixture. Either the fuel or oxidizer was dumped into the other component. Overpressure at a distance of 10 ft was recorded. The results are presented in Figure 41 and Table XIV. Of 105 tests, 92 resulted in audible explosions. Overpressures were recorded on 28 tests.

Test data in these experiments resulted in considerable scatter, similar to the results of the small tests. Uncontrolled factors contributing to this variability probably were: contact area, mixing efficiency, and vapor concentration.

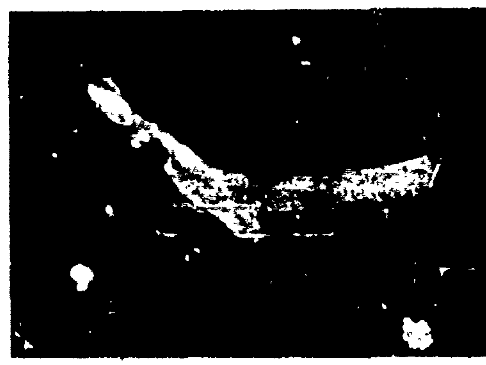
The tests using 3, 10, or 30 ml of mixture were conducted with a 3-in diameter pan and a dump height of 8 in. Six of nine samples with 3 ml of the 50:50 mixture dumped into liquid nitrogen tetroxide exploded. No pressure traces were obtained. Forty-seven of fifty-six tests with 10 ml of the mixture resulted in explosions with various degrees of severity. Overpressures were recorded on six tests. Although some explosions were below the lower limit of the instrumentation sensitivity, 0.05 psi, others were not recorded because of instrumentation difficulties. The overpressures ranged from 0.06 psi to 0.20 psi at 10 ft. The standard side-on pressure curves for TNT, if extrapolated to small pressures, indicate overpressures equivalent to 0.002 and 0.065 gm of TNT respectively.



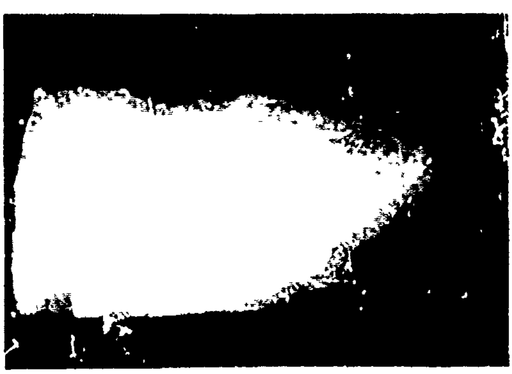
11 Milliseconds Before Explosion

15 Milliseconds Before Explosion

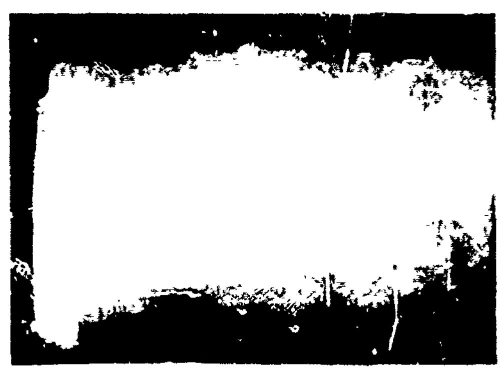
0.7 Millisecond Before Explosion



0.34 Millisecond Before Explosion

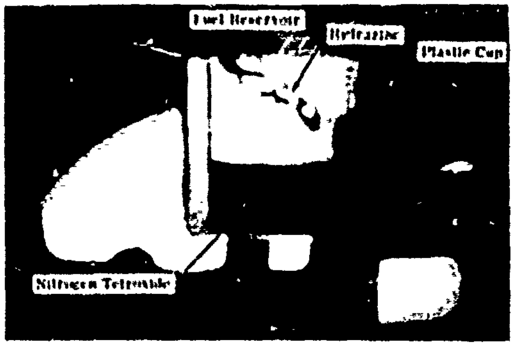


Explosion

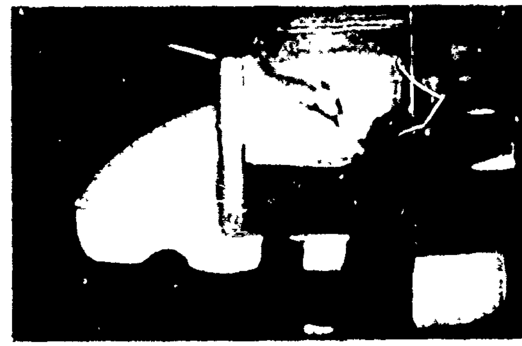


0.37 Millisecond After Explosion

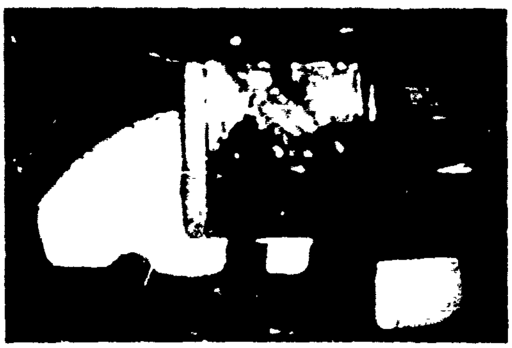
Figure 39. HYPERGOLIC REACTION BETWEEN LIQUID HYDRAZINE AND LIQUID NITROGEN TETROXIDE BEFORE CONTACT



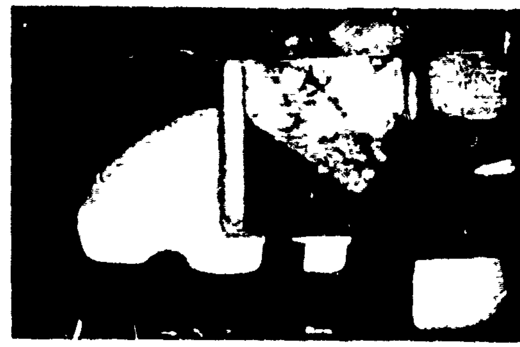
15 Millisecond Before Contact



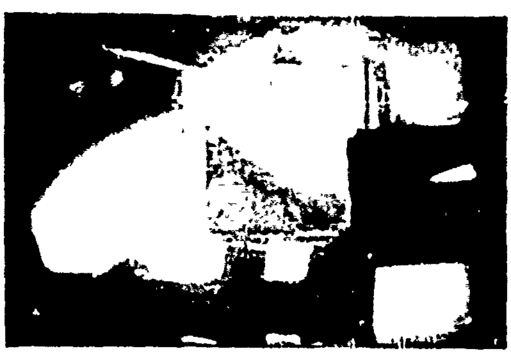
Contact—82 Milliseconds Before Explosion



21 Milliseconds Before Explosion



0.70 Millisecond Before Explosion



0.35 Millisecond Before Explosion

Explosion

Figure 40. HYPERGOLIC REACTION BETWEEN LIQUID HYDRAZINE AND LIQUID NITROGEN TETROXIDE AFTER CONTACT

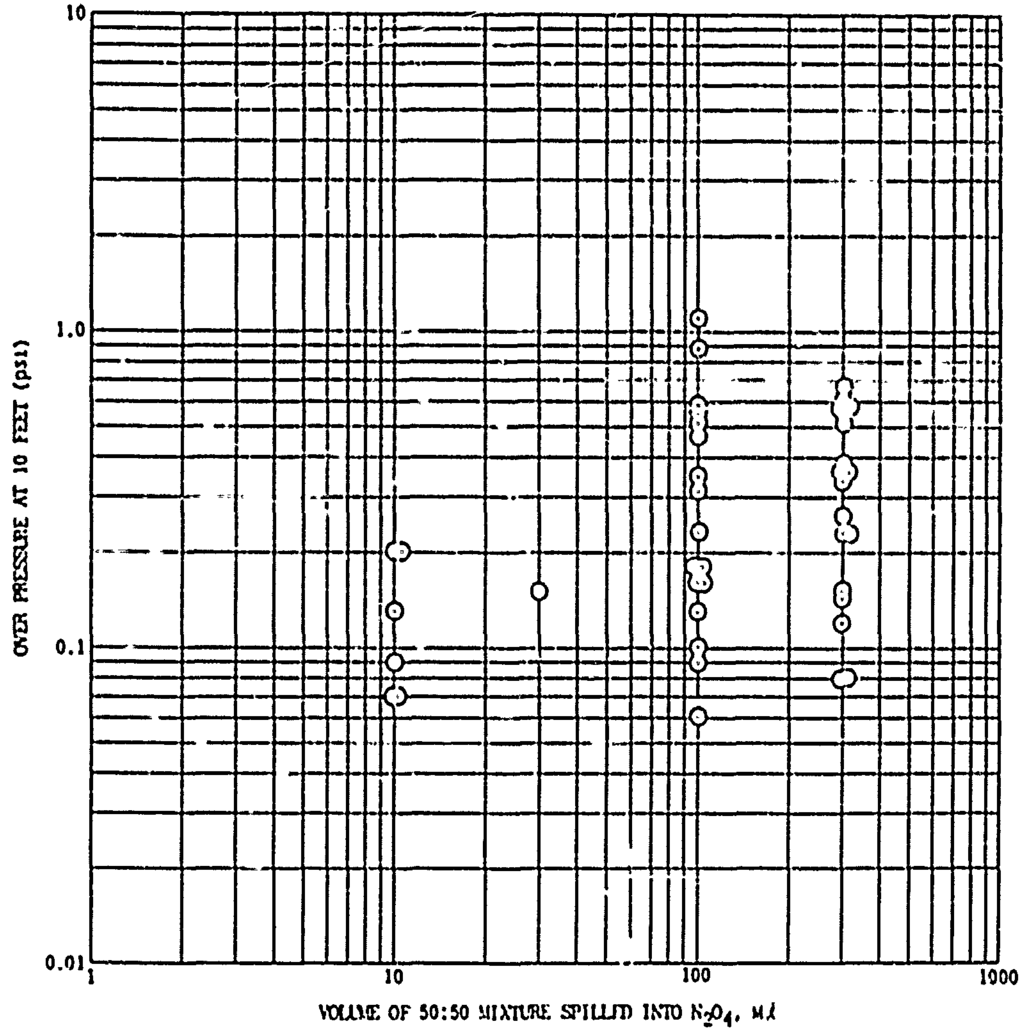


Figure 41. OVERPRESSURES FROM SPILLS INVOLVING 50:50 MIXTURE AND NITROGEN TETROXIDE

TABLE XIV

Overpressures Recorded When 50:50 Mixture Spilled into Liquid Nitrogen Tetroxide

Test No.	Volume Fuel (ml)	Volume Oxidizer (ml)	Explosion Intensity (Overpressure at 10 ft, psi)	Time Between Overpressures (milliseconds)
37	10	50	0.20	
41	10	50	0.20	
43	10	50	0.05[a]	
46	10	50	0.18[b]	
53	10	50	0.44[b]	
58	10	50	0.09	
60	10	50	0.13	
68	10	50	0.06	
69	10	50	0.06	
88	30	50	0.15	
32	90	150	0.23[a]	
--			0.23[a]	100
42	100	200	0.29[a]	
89	100	200	0.23	
--			0.88	90
90	100	200	0.09	
--			0.16	230
91	100	200	0.10	
--			0.51	50
--			0.46	230
92	100	150[c]	0.06	
--			1.10	600
93	100	150	0.31	
99	100	200	0.16	
--			0.55	50
100	100	200	0.18	
--			0.35	275

TABLE XIV cont'd

Test No.	Volume Fuel (ml)	Volume Oxidizer (ml)	Explosion Intensity (Overpressure at 10 ft, psi)	Time Between Overpressures (milliseconds)
117	100	200	0.18	
--			0.13	750
118	100	200	0.58	
113	300	200	0.36	
--			0.36	138
--			0.58	277
115	300	200	0.26	
--			0.60	50
--			0.51	51
116	300	420	0.38	
--			0.66	185
--			0.14	185
119	300	400	0.58	
120	300	400	0.55	
--			0.23	370
121	300	400	0.12	
--			0.57	90
--			0.33	690
122	300	350[c]	0.15	
--			0.08	185
--			0.08	325
--			0.23	240

a. Overpressure measured at 20 ft.

b. Overpressure measured at 5 ft.

c. Oxidizer spilled into fuel.

Although only one trace was obtained when 30 ml of the mixture were spilled into nitrogen tetroxide, 14 out of the 15 trials exploded The overpressure was 0.146 psi at 12 ft. The majority of the explosions sounded louder than those with 10 ml of fuel.

Twenty-five tests with 60, 90, 100, and 300 ml of fuel were conducted with an 8-inch diameter pan. The fuel or oxidizer was dumped from a height of 18 inches. Because of the larger size and increased height, all samples exploded. Overpressures were recorded from 18 of these tests.

All of 12 tests using 100 ml of the 50:50 mixture resulted in explosions. In contrast to the smaller scale tests, most of the spills resulted in two distinct explosions, 50 to 750 milliseconds apart. The largest overpressure varied between 0.16 and 1.1 psi. The TNT equivalent for this range is 0.035 to 9 gm.

All of eight tests in which 300 ml of the 50:50 mixture were spilled resulted in explosions. The overpressures recorded at 10 feet ranged from 0.03 to 0.66 psi. In most cases, three separate overpressure peaks were recorded. Similarly, the spill tests conducted at Edwards Air Force Base by Rocketdyne resulted in as many as 12 overpressure peaks when 300 lb of total propellant were spilled in a configuration which would promote splattering of the liquids rather than a broad area of contact. Photographs of two of these tests, along with the respective pressure trace, are shown in Figures 42 and 43.

As seen from Figure 42, when fuel was spilled into oxidizer in test 116 an explosion occurred immediately upon contact of the two liquids (frame No.2), after 185 milliseconds (frame No. 5), and after 370 milliseconds (frame No. 8). The reaction was essentially complete after one second. The oscilloscope record for this test is also shown in Figure 43. The oscilloscope beam moved from the right to the left at a rate of 1.3 in/milsec and the film was moved from the right to the left at a rate of 2.4 in/sec. The oscilloscope beam was deflected 1.25 in/psi overpressure.

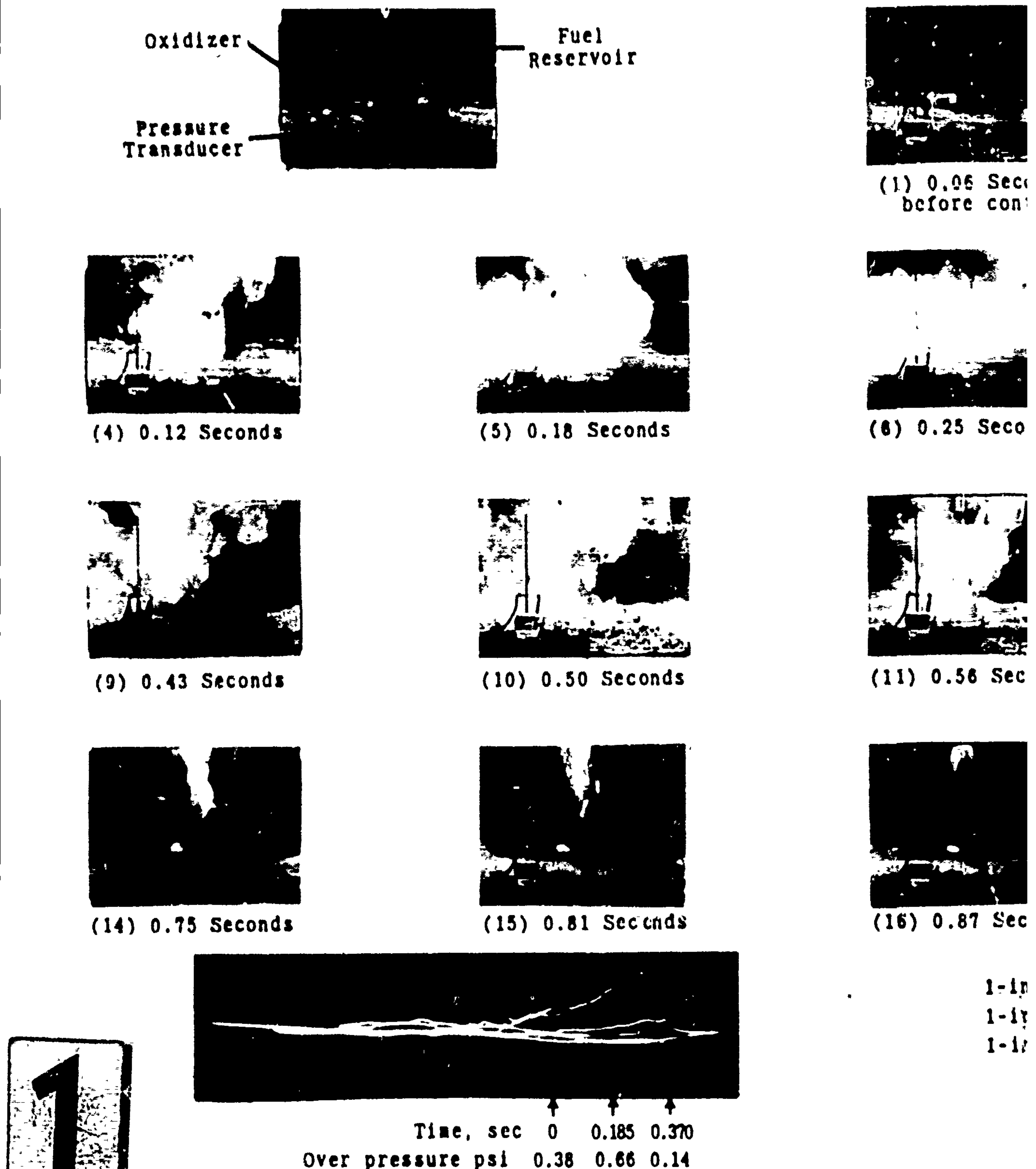
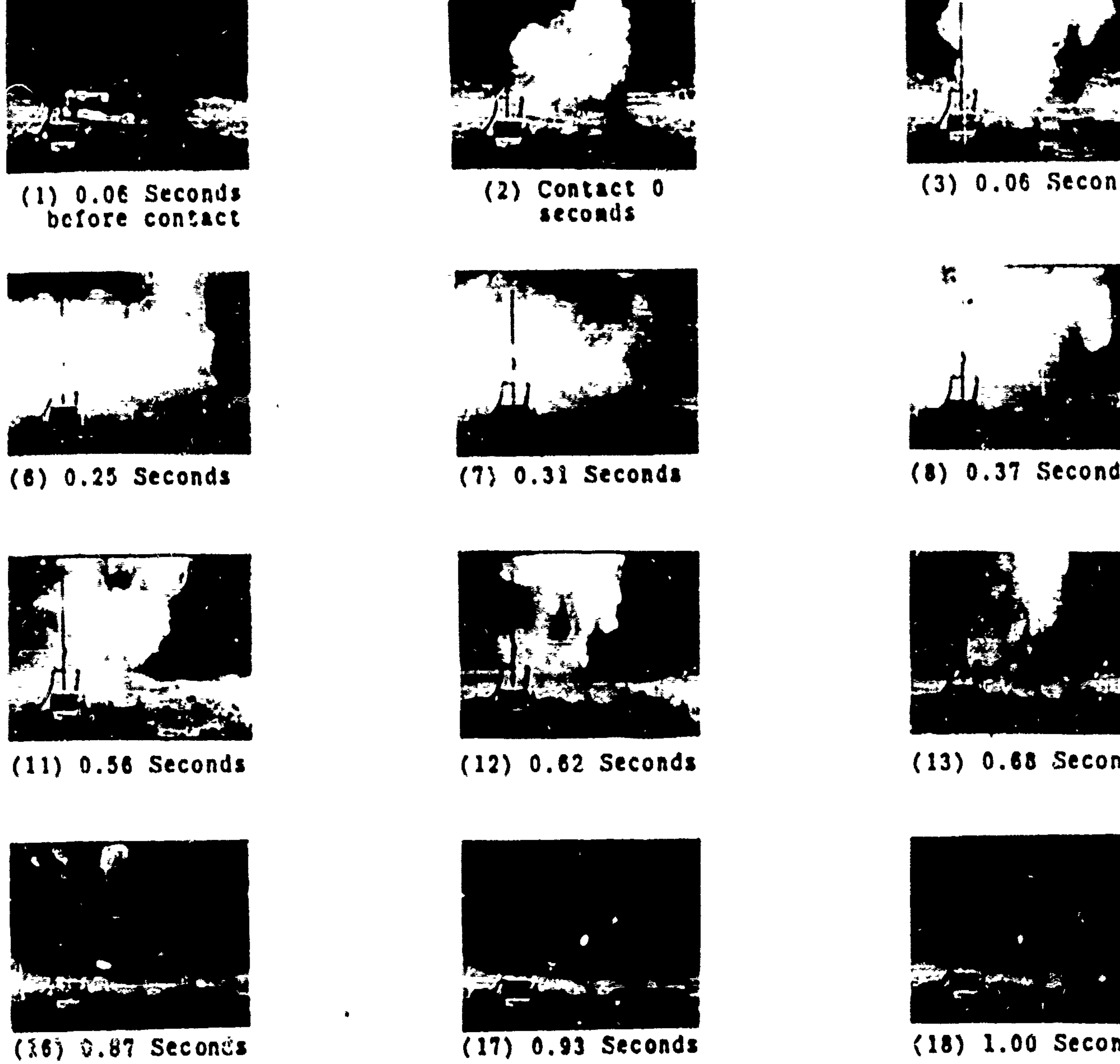


Figure 42. TEST NO.
MIXTURE
NITROGEN
SPEED 16



1-inch of deflection equals 1.5 psi
1-inch of trace equals 0.77 milliseconds
1-inch of film equals 420 milliseconds

Figure 42. TEST NO. 116, 300 ml 50:50 MIXTURE SPILLED INTO 420 ml NITROGEN TETROXIDE, CAMERA SPEED 16 FRAMES/SECOND

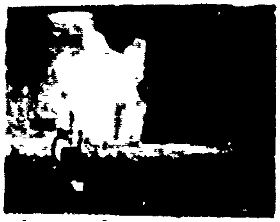
(1) 0.12 Seconds
before contact

(2) 0.06 Seconds
before contact

(3) Contact 0
seconds

(4) 0.06 S

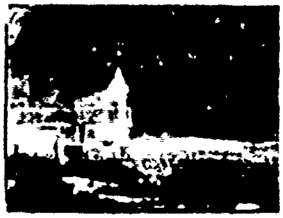
(7) 0.25 Seconds



(8) 0.31 Seconds

(9) 0.37 Seconds

(10) 0.43 S



(13) 0.62 Seconds

(14) 0.68 Seconds

(15) 0.75 Seconds

(16) 0.81 S

Time, sec	0	185	510	750
Over pressure psi	0.15	0.08	0.08	0.23

1-inch of deflect
1-inch of trace e
1-inch of film eq

Figure 43. TEST NO. 122, 350 ml NITROGE
TETROXIDE SPILLED INTO 300 m
50:50 MIXTURE CAMERA SPEED
16 FRAMES/SECOND

t 0
s

(4) 0.06 Seconds

(5) 0.12 Seconds

(6) 0.18 Seconds

econds

(10) 0.43 Seconds

(11) 0.50 Seconds

(12) 0.56 Seconds

econds

(16) 0.81 Seconds

(17) 0.87 Seconds

(18) 0.93 Seconds

1-inch of deflection equals 0.8 psi
1-inch of trace equals 0.67 milliseconds
1-inch of film equals 425 milliseconds

2

T NO. 122, 350 ml NITROGEN
ROXIDE SPILLED INTO 300 ml
50 MIXTURE CAMERA SPEED
FRAMES/SECOND

When nitrogen tetroxide was spilled into the 50:50 mixture in test number 122, the results shown in Figure 42 were obtained. A sharp overpressure occurred upon contact of the liquids, two gradual overpressures occurred at 185 and 510 milliseconds, and a final sharp overpressure at 750 milliseconds. This reaction was also essentially complete within one second after contact.

Because the fuel and oxidizer exploded on contact, extinguishment was not attempted. In every case the burning time was less than one second.

A series of tests was made to determine if the explosions could be suppressed. The technique used and the test results are presented in Table XV. A 1:1 dilution of nitrogen tetroxide by water in the burner pan suppressed the explosion and fire. However, when the amount of water was reduced the samples exploded when either fuel or oxidizer was dumped. Water would be a practical suppressant in large quantities if mixing of the water and propellant were assured.

Because sodium bicarbonate satisfactorily extinguished fires oxidized by air, it was tested as a suppressant. However, when a 1/8-inch-thick layer of sodium bicarbonate was placed over the 50:50 mixture in the pan before nitrogen tetroxide was dumped, the two liquids exploded upon contact.

The explosions were attenuated but not suppressed by sand in the burner before the liquids were spilled. Although the sand prevented intimate contact of the two liquids, on reaction the sand containing the other component was thrown out.

(3) Silo Tests with the 50:50 Mixture

Seven tests with liquid nitrogen tetroxide were completed in the Titan II model silo. The results are shown in Table XVI. When 155 ml of nitrogen tetroxide were dumped into 115 ml (0.465-inch depth) of 50:50 mixture, the explosion resulted in a pressure of 30 psi in the silo

TABLE XV

Suppression of Hypergolic Explosions

Test No.	Volume of Fuel (ml)	Volume of Oxidizer (ml)	Suppressant	Result (Explosion)	Overpressure at 10 ft (psi)
101	100[a]	200	200 ml water	No	--
102	100[a]	200	200 ml water	No	--
103	100[a]	200	100 ml water	Yes	0.25
104	100	150[a]	100 ml water	Yes	0.31
105	100	150[a]	1/8 inch sodium bicarbonate	Yes	--
106	100	150[a]	3/4 inch sand	Small	--
107	100	150[a]	1/4 inch sand	Small	--
108	100[a]	200	1/2 inch sand	Small	--
109	100[a]	200	3/4 inch sand	Small	--
110	100[a]	200	3/4 inch sand	Small	0.13
111	300[a]	200	3/4 inch sand	Small	--
112	300[a]	200	3/4 inch sand	Small	--

a. Component dumped.

TABLE XVI

Silo Tests with Hypergolic Liquids[a]

Test No.	Component Dumped	Suppressant	Result (Explosion)	Silo Pressure (psi)	Overpressure at 10 ft (psi)
123	Oxidizer	None	Yes	30	0.25
124	Oxidizer	100 ml water	Small	--	--
125	Oxidizer	50 ml water	Yes	--	0.12
126	Fuel	None	Yes	--	0.25
127	Oxidizer	1/8 inch Sodium bicarbonate	Yes	30	--
128	Oxidizer	3/4 inch Sand	Burned	--	--
129	Fuel	3/4 inch Sand	Yes	--	--

a. 115 ml 50:50 mixture and 115 ml nitrogen tetroxide.

and 0.25 psi at a distance of 10 ft. Addition of 100 ml of water to the 50:50 mixture reduced the explosive intensity. No overpressures were recorded.

When 50 ml of water were added to the mixture, the explosion sounded as loud as that containing no water. No overpressures were recorded. Addition of a 1/8-inch layer of sodium bicarbonate on top of the 50:50 mixture did not attenuate the explosion. A 0.75-inch layer of sand prevented an explosion when the oxidizer was spilled into the fuel but failed to suppress it when the fuel was spilled into the oxidizer. These last two tests were the only ones in which the fire continued to burn.

VII. CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations based on results from specific fuel fires are as follows:

(1) Hydrazine fires oxidized by air can be extinguished by water sprays, alcohol-type foams, or dry chemical powders containing primarily sodium bicarbonate. Water sprays are best suited and are recommended for spill-type fires. Foams are recommended for deep pools or in cases where the water supply is limited. Dry chemicals are preferred when rapid extinguishment is necessary or when the amount of agent available is limited, provided, in any case, that reignition is not a problem. Chlorobromomethane is unsuitable against hydrazine fires. Hydrazine fires oxidized by nitrogen tetroxide vapors require at least twice as much water for extinguishment as when oxidized by air.

(0) UDMH fires can be extinguished by water sprays, alcohol-type foams, dry chemical powders containing primarily sodium bicarbonate, or trichlorotrifluoroethane (Freon 113). Water sprays are best suited for spill-type fires. Foams are especially suitable against either spill-type or deep pool fires. Dry chemicals are preferred when rapid extinguishment is necessary or when the supply of agent is limited, providing reignition is not a problem.

(3) JP-X fires can be extinguished by alcohol-type foams or dry chemical agents containing primarily sodium bicarbonate. Foams recommended when reignition hazards are a problem. Water spray is ineffective against JP-X fires.

(4) Hydrazine-UDMH fires (50:50 mixture) behave essentially as UDMH fires. Approximately the same types and quantities of extinguishing agents are recommended. Water sprays, alcohol-type foams, or sodium bicarbonate dry chemical powders are effective against fires involving the 50:50 mixture in either a spill-type or a silo configuration. Neither bromotrifluoromethane nor carbon dioxide are effective. Ordinary mechanical foams such as Jan-C-266, are only slightly more effective than water sprays.

(5) Fires Involving Liquid Nitrogen Tetroxide
Any of the hydrazine-type fuels can explode upon contact with liquid nitrogen tetroxide. Until the appropriate scaling factors and parameters affecting the intensities of the explosions are determined, such fires should be approached with caution and only with adequate safety equipment.

(6) Reactions of Hydrazine-Type Fuels with Liquid Nitrogen Tetroxide

Hydrazine-type fuels react explosively with liquid nitrogen tetroxide in most instances. While maximum explosive yields were obtained in relatively small samples no agent was found nor can one be recommended on the basis of experimental results that could be used to adequately suppress the hypergolic explosion after the components were mixed. Water in sufficient concentrations as a diluent of either liquid prior to mixing suppresses the explosive reaction.

The rates and amounts of agents recommended for extinguishing fires involving the hydrazine-type fuels in air are presented in Table XVII.

TABLE XVII

Extinguishment of Fires Involving Hydraz

Summary of Results of Pan Tes

	Extinguishing Agent[a]					
	Water Spray			Alcohol Foam		
Fuel	Application[b] Rate (gpm/sq ft)	Amount[c,d] Required (gal water / gal fuel)	Time[e] Required (min/in fuel)	Application[f] Rate (gpm/sq ft)	Amount[f] Required (gal liq/sq ft)	i
Hydrazine	0.8	1.0	0.78	0.4	0.1	
UDM.	0.8	2.5	1.95	0.4	0.25	
50:50 mixture of hydrazine - UDMH	0.8	2.0	1.56	0.4	0.15	
JP-X	0.8	Not satisfactory		0.4	0.16	

a. Amounts shown are actual requirements and do not include any safety factor.
b. Recommended rate of application per square foot of fire (use maximum rate available).
c. Minimum amount of agent required per gallon of fuel spilled.
d. Twice as much agent is required for fires oxidized by nitrogen tetroxide vapors.
e. Time required for extinguishment per inch of fuel depth when agent is applied at rate indicat
f. Based on gallons of liquid contained in the foam.
g. Time required for extinguishment when agent is applied at the indicated rate so as to cover th

Note:
1. Hydrazine at initial temperature of 140°F, UDMH, 50:50 mixture and JP-X at intial temperature
2. Ten-second preburn time was used in all tests which were air oxidized unless otherwise noted.
3. Water spray should be coarse, 600 micron average drop size.
4. A 6 per cent alcohol foam was used with a 10:1 expansion ratio. Ordinary foams were ineffecti
5. The dry chemical was primarily sodium bicarbonate. Potassium bicarbonate was equally effectiv

TABLE XVII

ires Involving Hydr..ine-Type Fuels

of Results of Pan Tests

tinguishing Agent[a]					
Alcohol Foam		Dry Chemical			
Amount[f] Required (gal liq/sq ft)	Time[g] Required (min)	Application Rate (lb/sq ft-sec)	Amount Required (lb/sq ft)	Time[g] Required (min)	Remarks
0.1	0.25	0.02	0.04	0.033	Chlorobromomethane is ineffective reacts with hydrazine
0.25	0.625	0.02	0.10	0.083	Trichlorotrifluoroethane is twice as effective per pound as water spray
0.15	0.375	0.02	0.10	0.083	Bromotrifluoromethane and carbon dioxide are both ineffective
0.16	0.40	0.02	0.10	0.083	

r.
available).

vapors.
lied at rate indicated so as to cover entire burning surface.

ate so as to cover the entire burning surface.

at intial temperature of 80°F.
ess otherwise noted.

foams were ineffective.
was equally effective.

2

VIII. FUTURE WORK

To extend the scope of fire extinguishment analysis and study of hydrazine-type fuels, we recommend that additional work be directed towards the following:

(1) Characterize diluent and dilutions necessary to prevent fire in enclosed spaces. The diluent concentration (or the required reduction in oxidizer vapors concentration) necessary in the gas phase to prevent fire in the liquid phase (or vice versa), should be determined.

(2) Develop means to monitor air in or near the missile where run-off is likely if propellant were spilled.

(3) Define more accurately the parameters (and their values) affecting the intensities and scaling of explosions between hydrazine-type fuels and liquid nitrogen tetroxide, and extend these data to relate the most effective action to specific situations.

(4) Institute a program to develop preventive safety measures by early-warning hazards control. We recommend that detection systems be developed for accurate, reliable, and continuous monitoring of fuel and oxidizer concentrations in and around the missile and silo to initiate, if maximum tolerable limits are exceeded, a deluge or other system to intercede a potential fire hazard as soon as possible after it develops. Explosion and flammability limits would be incorporated into the design of a detector system for continuous use in critical areas during handling and storage. Engineering development would include studies to determine the detector response required in specific situations. The geometrical requirements of the system relative to the potential source, the time lag between detection and action, and the amount and timing of various actions which could be taken to effectively control or completely eliminate the hazard.

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APPENDIX

EXPERIMENTAL EXTINGUISHMENT DATA FOR FIRES OF HYDRAZINE-TYPE FUELS

Table I summarizes the burning times (with averages), for fires of Hydrazine, UDMH, 50:50 mixture, and JP-X at various depths and fire areas.

Tables II through XLIV include extinguishment data for various agents applied at different rates to fires of these same four fuels. Averages for duplicate determinations, and, in most cases, the composition of the remaining liquid are shown.

Tables I and XVII (main body of this report), summarize the overall results, and the recommendations for various fuels, based on the experimental data in the Appendix.

TABLE I BURNING TIMES OF VARIOUS FUELS IN VARIOUS SIZES OF BURNERS[a]

Fuel depth (inches)	Hydrazine 6.3[b]	49	324	UDMH 6.3	49	324	50-50 Mixture 6.3	49	324	3304	JP-4 6.3	49	324
0.093	46.9	49.8		143.4			125				247		
	47.1	49.4		149.4			129				240		
	51.0			151.2			127				239		
	41.9			148.3			126				244		
	51.8			149.0			127				248		
Average	(47.8)[c]	(49.6)		(148.2)			(127)				(244)		
0.186	52.0	65.0		257.2	320		188				379	480	
	53.2	64.2		257.8	322		184				378	500	
	56.0	68.6		260.6	323		181				380	490	
	54.0	68.0		260.2			186				383		
	54.5			257.5			185				380		
Average	(53.9)	(66.4)		(258.5)	(322)		(185)				(380)	(490)	
0.279	59.0	74.0	90.0	323.6	446	370	257	213	297		520	615	490
	62.9	74.0	87.0	322.0	448	372	260				522	624	490
	61.2	72.2		324.0	448		259				521	620	
	62.6	72.2		321.2			265				520		
	63.1			323.8			258				512		
Average	(61.8)	(73.1)	(88.0)	(322.9)	(448)	(371)	(259)				(519)	(620)	(490)
0.372		88.0	95.0	384.0	555	380	335	271	339		650	763	520
		86.2	94.0	384.8	561	380	330				652	758	518
		90.0		380.0	551		334				647	765	
		89.2		389.4			338				655		
				381.2			336				653		
Average		(88.4)	(94.5)	(383.9)	(556)	(380)	(335)				(651)	(762)	(519)
0.465		98.0	98.0		610	392		309	366			895	550
		97.6	98.0		623	395						900	555
					600	460						900	
						452							
Average		(97.8)	(98.0)		(611)	(425)						(898)	(552)
0.930						605							
						595							
						(600)							
0.53										305			
1.06										402			

a. Burning time in seconds.

b. Numbers below each fuel are fire areas in square inches.

c. Numbers in parentheses are averages for burning times at a given fuel depth.

TABLE II

Extinguishment of Hydrazine Fires in 6.5-Sq in Burner by Water Spray

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining Hydrazine (Volume per cent)	Average
0.093	0.20	7.0		53.2	
	0.20	7.6	7.3	47.7	50.4
	0.425	6.0		48.5	
	0.425	5.6	5.8	50.3	49.4
	0.70	4.0		62.1	
	0.70	3.8	3.9	61.1	61.6
	0.86	2.8		57.5	
	0.86	2.6	2.7	63.1	60.3
	1.17	2.2		58.4	
	1.17	2.6	2.4	57.4	57.9
0.186	0.20	15.0		56.2	
	0.20	15.4	15.2	58.5	57.4
	0.30	17.0		55.6	
	0.30	7.3		70.0	
	0.30	8.7		57.1	
	0.30	8.1	8.0	63.6	63.6
	0.37	5.0		-	
	0.37	4.8		-	
	0.37	7.3		-	
	0.37	7.4		-	
	0.37	9.8		-	
	0.37	10.3	7.4	-	
	0.425	8.6		76.0	
	0.425	9.2	8.9	74.5	75.2
	0.70	5.8		81.0	
	0.70	6.0	5.9	81.4	81.2
0.186	0.86	5.4		60.5	
	0.86	6.0		60.0	
	0.86	4.8		61.0	
	0.86	2.0		80.6	
	0.86	5.8	5.5	66.2	61.9
	1.17	2.2		58.4	
	1.17	2.6	2.4	57.4	57.9
0.279	0.20	22.0		66.0	
	0.20	22.0	22.0	68.0	67.0
	0.425	12.2		78.8	
	0.425	11.6	11.9	73.4	76.1
	0.70	8.0		80.5	
	0.70	7.6	7.8	79.0	79.7
	0.86	7.0		63.1	
	0.86	7.6	7.3	62.0	62.6
	1.17	5.8		80.9	
	1.17	5.4	5.6	79.4	80.2

TABLE II (CONT)

Extinguishment of Hydrazine Fires in 6.5-Sq in Burner by Water Spray

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining Hydrazine (Volume per cent)	Average
0.372	0.20	39.0		68.0	
	0.20	40.0	39.5	68.5	68.2
	0.425	14.4		85.5	
	0.425	14.8	14.6	85.5	85.5
	0.70	9.8		90.4	
	0.70	10.0	9.9	90.7	90.6
	0.86	7.9		69.5	
	0.86	9.0		67.1	
	0.86	7.4	8.0	71.1	69.2
	1.17	6.8		85.1	
	1.17	7.0	6.9	86.2	85.6

TABLE III

Extinguishment of Hydrazine Fires in 49-Sq in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining Hydrazine (Volume per cent)	Average
0.186	0.21	17.0		49.9	
	0.21	18.4		49.7	
	0.21	17.4	17.6	49.9	49.8
	0.42	8.9		53.0	
	0.42	9.4		52.0	
	0.42	9.6		52.0	
	0.42	10.0		51.6	
	0.42	9.2	9.4	52.4	52.2
	0.59	7.6		38.6	
	0.59	7.4		40.0	
	0.59	7.8		39.6	
	0.59	7.4	7.5	40.5	39.7
	0.82	6.2		43.0	
	0.82	6.6		42.7	
	0.82	6.2	6.3	42.7	42.8
0.279	0.21	27.0		51.5	
	0.21	26.8		51.5	
	0.21	27.0	26.9	51.5	51.5
	0.42	13.9		54.4	
	0.42	13.8		54.4	
	0.42	14.2		52.6	
	0.42	14.8		52.0	
	0.42	14.0	14.1	52.6	53.2
	0.59	9.8		50.5	
	0.59	10.4		48.5	
	0.59	11.0		47.7	
	0.59	10.6	10.5	48.5	48.8
	0.82	9.4		50.0	
	0.82	9.2		50.1	
	0.82	9.6	9.4	50.0	50.1
0.372	0.21	34.6		56.0	
	0.21	35.0		56.4	
	0.21	34.8	34.8	56.0	56.1
	0.42	18.4		55.4	
	0.42	20.8		52.6	
	0.42	19.6		55.0	
	0.42	19.6		53.6	
	0.42	18.0	19.2	56.2	54.5
	0.59	14.6		55.0	
	0.59	14.6		55.0	
	0.59	14.0		54.7	
	0.59	13.0	14.0	54.7	54.8
	0.82	14.0		50.1	
	0.82	11.2		52.9	
	0.82	12.0	12.4	52.5	51.8

TABLE III (CONT)

Extinguishment of Hydrazine Fires in 49-Sq in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining Hydrazine (Volume per cent)	Average
0.465	0.21	42.0		63.0	
	0.21	43.0		60.2	
	0.21	41.8	42.3	63.0	62.6
	0.425	23.2		57.5	
	0.425	22.7		56.2	
	0.425	22.6		56.2	
	0.425	22.0		57.5	
	0.425	23.2	22.7	57.2	54.2
0.465	0.59	18.0		54.7	
	0.59	16.8		56.5	
	0.59	17.2		56.2	
	0.59	17.0	17.3	56.2	55.9
	0.82	14.8		53.6	
	0.82	16.0		52.5	
	0.82	15.4	15.4	53.2	53.1

TABLE IV

Extinguishment of Hydrazine Fires in 324-Sq in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration Remaining Hydrazine (Volume per cent)	Average
0.279	0.6	20.0		45.4	
	0.6	22.0		45.6	
	0.6	21.2		33.3	
	0.6	21.0	21.0	33.5	39.5
	0.8	7.0		44.3	
	0.8	8.0		44.3	
	0.8	10.0		43.1	
	0.8	8.0	8.2	41.9	43.4
0.372	0.6	24.0		49.1	
	0.6	25.0		48.6	
	0.6	24.4		33.7	
	0.6	24.8	24.5	34.8	41.3
	0.8	13.0		57.6	
	0.8	13.0		57.0	
	0.8	13.0		30.0	
	0.8	13.2	13.0	34.9	44.9
0.465	0.6	27.0		53.4	
	0.6	27.0		55.2	
	0.6	27.0		39.3	
	0.6	26.8	27.0	40.9	47.2
	0.8	17.0		60.9	
	0.8	17.0		60.9	
	0.8	16.4		39.4	
	0.8	17.0	16.9	39.7	50.2

TABLE V

Extinguishment of Hydrazine Fires in 6.5-Sq in Burner by Foam

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining Hydrazine (Volume per cent)	Average
0.093	0.30	10.0		54.2	
	0.30	9.2	9.6	55.0	54.6
0.186	0.13	34.2		-	
	0.13	42.4	38.3	-	
	0.30	15.4		58.5	
	0.30	14.6	15.0	59.5	59.0
	0.33	12.8		-	
	0.33	14.2		-	
	0.33	11.6	12.9	-	
0.279	0.29	15.7		72.8	
	0.29	20.2	18.0	65.7	67.2
0.372	0.30	18.0		74.0	
	0.30	16.0	17.0	74.5	74.2

TABLE VI

Extinguishment of Hydrazine Fires in 49-Sq in Burner by Foam

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining Hydrazine (Volume per cent)	Average
0.186	0.2	18.0		61.4	
	0.2	16.4		61.4	
	0.2	19.2	17.9	61.9	61.6
	0.32	7.0		77.5	
	0.32	8.0		75.7	
	0.32	7.6	7.5	76.3	76.5
0.279	0.20	20.0		63.0	
	0.20	22.8		62.5	
	0.20	21.6	21.5	61.0	62.2
	0.32	12.0		77.5	
	0.32	11.0		78.0	
	0.32	12.0	11.7	76.7	77.4
0.372	0.20	22.0		61.9	
	0.20	25.0		66.2	
	0.20	24.4	23.8	66.6	64.9
	0.32	15.0		81.0	
	0.32	14.0		83.6	
	0.32	13.8	14.3	83.6	82.7
0.465	0.20	25.8		76.7	
	0.20	27.0		67.2	
	0.20	27.6	26.8	68.2	67.7
	0.32	18.0		85.9	
	0.32	18.0		86.4	
	0.32	19.0	18.3	85.3	85.9

TABLE VII

Extinguishment of Hydrazine Fires in 324-Sq in Burner by Foam

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining Hydrazine (Volume per cent)	Average
0.465	0.4	9.2		94.5	
	0.4	9.0	9.1	85.9	90.2
0.558	0.4	11.6		95.8	
	0.4	11.8	11.7	94.5	95.1
0.651	0.4	12.0		96.4	
	0.4	12.4	12.2	94.8	95.6

TABLE VIII

Extinguishment of Hydrazine Fires in 6.5-Sq in Burner[a] by Sodium Bicarbonate

Fuel Depth (inches)	Application Rate (lb/sec/sq ft)	Extinguishment Time (Seconds)	Average
0.093	0.016	3.0	
		2.9	3.0
	0.047	1.0	
		1.5	1.2
	0.062	1.2	
		1.5	1.4
	0.096	1.4	
		1.6	1.5
0.186	0.016	3.0	
		1.5	2.2
	0.047	1.8	
		2.0	1.9
	0.062	1.5	
		1.6	1.6
	0.096	1.8	
		0.9	1.4
0.279	0.016	1.5	
		2.5	2.0
	0.047	2.1	
		2.8	2.5
	0.062	1.4	
		1.6	1.5
	0.096	0.7	
		1.0	0.8

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a. 0.0245 lb/sq ft of sodium bicarbonate or potassium bicarbonate, such as Fyr-Fyter "Purple K", applied rapidly extinguished 6.5-sq in fires immediately. 0.0194 lb/sq ft of sodium or potassium bicarbonate failed to extinguish 6.5-sq in fires. 0.049 lb/sq ft of ABC powder failed to extinguish 6.5-sq in fires. ABC powder, such as "Alim ABC", applied at a rate of 0.033 lb-sq ft/sec, extinguished 6.5-sq in fires in 15 - 20 seconds.

TABLE IX

Extinguishment of Hydrazine Fires in 49-Sq in Burner by Sodium Bicarbonate

Fuel Depth (inches)	Application Rate (lb-sq ft/sec)	Extinguishment Time (Seconds)	Average
0.186	0.0083	2.0	
		1.0	
		1.0	1.3
	0.0175	4.0	
		2.0	
		2.6	2.9
0.279	0.0083	1.4	
		1.0	
		2.2	1.5
	0.0175	no ext	
		3.0	
		3.2	3.1
0.372	0.0083	no ext	
		2.2	
		1.8	2.0
	0.0175	no ext	
		4.4	
		4.0	4.2
0.465	0.0083	2.4	
		1.0	
		1.8	1.7
	0.075	2.6	
		4.0	
		4.8	3.8

TABLE X

Extinguishment of Hydrazine Fires in 324-Sq in Burner by Sodium Bicarbonate

Fuel Depth (inches)	Application Rate (lb-sq ft/sec)	Extinguishment Time (Seconds)	Average
0.279	0.016	0.8	
		1.6	1.2
0.372	0.016	1.0	
		1.2	1.1
0.465	0.016	1.2	
		1.0	1.1

TABLE XI

Extinguishment of Hydrazine Fires by Various Other Agents

Agent	Fire Size (Sq in)	Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining Hydrazine (Volume per cent)	Average
Water Fog	6.5	0.093	0.23	13.0		51.6	
				13.1	13.1	51.5	51.5
		0.186		12.0		79.5	
				12.0		67.2	
				10.4		66.6	
				20.0		57.8	
				20.0	14.9	-	57.8
		0.279		21.6		71.0	
				25.0		68.8	
				19.5	22.0	70.5	70.1
Water Fog	49	0.186	0.20	40.6		51.9	
				40.0		51.6	
				38.0	39.5	53.2	51.6
		0.279		75.0		51.6	
				77.8		56.4	
				71.8	74.9	51.3	53.1
		0 372		113.0		50.8	
				105.0		50.8	
				110.0	109.3	53.8	51.8
		0.465		133.0		53.0	
				130.0		53.2	
				135.0	132.7	52.5	52.9
8 Weight per cent Sodium Bicarbonate Solution	6.5	0.186	0.60	7.5		8.4[a]	
				7.9		7.8[a]	
				6.9		7.8[a]	
				8.0		8.6[a]	
				7.8	7.6	7.8[a]	8.1

[a] Plain water applied under similar conditions

TABLE XI (CONT)

Extinguishment of Hydrazine Fires by Various Other Agents

Agent	Fire Size (Sq in)	Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining Hydrazine (Volume per cent)	Average
Solid water stream	6.5	0.093	0.37	17.6		26.2	
				22.6		22.4	
				20.2	20.1	22.7	24.1
		0.186		46.4		20.6	
				35.6		23.3	
				41.8	41.2	21.0	21.6
		0.279		60.4		25.9	
				56.2		27.8	
				48.2	55.0	29.4	27.7
Horizontal Water spray	6.5	0.093	0.42	5.1		54.0	
				8.8		40.5	
				11.6		38.0	
				8.6	8.4	39.2	42.9
		0.186		12.2		51.0	
				11.7		51.0	
				12.6	12.2	60.2	54.1
		0.279		14.4		59.2	
				20.5		53.7	
				15.9	16.9	58.0	57.0
Chlorobromo-methane	6.5	0.093	0.1	no ext			
		0.186		no ext			
Carbon dioxide (gas)	6.5	0.186	0.17[b]	no ext			
		0.279	0.17[b]	no ext			

[b] Units of lb-sq ft/sec.

TABLE XII

Extinguishment of UDMH Fires in 6.5-Sq in. in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining (UDMH) (Volume per cent)	Average
0.093	0.20	21.0		43.6	
		22.0		43.6	
		24.0		43.6	
		21.2		43.6	
		23.8	22.4	43.6	43.6
	0.25	21.4		32.1	
		19.9		30.6	
		15.5		39.2	
		19.3		39.2	
		21.2	20.5	36.4	36.8
	0.41	17.1		28.3	
		15.4		27.8	
		17.1		29.2	
		16.9		28.8	
		17.0	16.7	30.6	28.9
	0.42	11.0		39.8	
		11.4		39.1	
		10.2		37.7	
		10.8		37.7	
		10.0	10.7	-	38.4
	0.50	10.7		34.6	
		10.8		32.4	
		11.5		32.0	
		11.4		35.0	
		9.0	10.7	40.8	34.8
	0.60	8.5		36.0	
		8.0		35.6	
		7.9		36.4	
		9.0		36.4	
		8.4	8.4	-	36.0
	0.80	6.4		32.1	
		6.6		34.0	
		6.4		31.4	
		6.4		31.5	
		6.8	6.6	31.4	32.1
	0.81	7.0		32.4	
		7.2		33.0	
		7.6		32.4	
		7.0		32.0	
		7.4	7.2	-	32.4
0.186	0.20	64.2		44.0	
		66.0		45.0	
		65.6		46.5	
		64.0		45.0	
		66.2	65.2	-	45.0

TABLE XII (CONT'D)

Extinguishment of UDMH Fires in 6.5-Sq in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining UDMH (Volume per cent)	Average
0.186	0.25	38.8		37.0	
(cont)		42.8		37.6	
		40.2		40.1	
		40.2		43.4	
		31.3	40.5	50.0	39.5
	0.41	23.2		34.3	
		23.0		36.1	
		24.0		35.0	
		22.6		34.3	
		22.8	23.1	35.0	34.9
	0.42	22.0		41.0	
		23.2		41.0	
		21.6		41.0	
		23.0		41.0	
		23.8	22.7	-	41.0
	0.50	21.0		40.4	
		21.6		38.1	
		22.1		40.0	
		20.8		41.2	
		21.2	21.3	42.3	40.4
	0.60	16.5		37.0	
		16.0		35.6	
		15.0		36.4	
		16.0		36.0	
		16.0	16.0	-	36.4
	0.80	8.4		37.2	
		8.2		37.7	
		9.0		36.0	
		8.8		38.2	
		8.5	8.6	36.3	35.5
	0.81	11.0		36.4	
		11.4		35.0	
		11.0		36.0	
		10.8		35.0	
		11.2	11.1	-	35.6
0.279	0.20	101.8		47.0	
		102.6		46.6	
		102.0		46.6	
		102.8		46.3	
		96.4	101.0	-	46.6
	0.25	62.3		45.8	
		69.4		45.4	
		70.0		43.1	
		67.8		43.1	
		65.0	66.9	41.8	44.0

TABLE XII (CONT'D)

Extinguishment of UDMH Fires in 6.5-Sq in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining UDMH (Volume per cent)
0.279	0.41	40.0		34.3
		28.8		35.8
		34.6		38.7
		31.4		46.0
		38.6		35.0
		29.5		39.4
		33.0	33.7	39.8
	0.42	38.0		43.6
		39.5		44.0
		36.0		44.5
		38.2		43.6
		36.8	37.7	-
	0.50	38.4		41.2
		29.6		41.2
		29.8		39.6
		30.2		38.1
		31.2	31.8	37.4
	0.60	25.6		38.4
		25.4		38.7
		24.0		38.7
		27.0		38.4
		26.0	25.6	-
	0.80	14.4		38.6
		14.0		39.5
		15.2		38.4
		14.8		37.7
		13.8	14.4	39.7
	0.81	14.9		41.6
		15.6		41.0
		15.6		41.6
		15.6		41.6
		15.4	15.4	-
0.372	0.20	139.2		47.0
		138.6		46.3
		136.0		47.3
		138.0		46.3
		140.0	138.4	-
	0.25	83.8		50.0
		84.0		48.5
		83.5		49.8
		85.0		47.7
		76.2	82.5	52.0
	0.42	48.2		43.6
		49.6		43.6
		51.0		43.3
		49.0		43.6
		49.8	49.5	-

TABLE XII (CONT'D)

Extinguishment of UDMH Fires in 6.5-Sq in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining UDMH (Volume per cent)	Average
0.279	0.41	40.0		34.3	
		28.8		35.8	
		34.6		38.7	
		31.4		46.0	
		38.6		35.0	
		29.5		39.4	
		33.0	33.7	39.8	38.5
	0.42	38.0		43.6	
		39.5		44.0	
		36.0		44.5	
		38.2		43.6	
		36.8	37.7	-	43.6
	0.50	38.4		41.2	
		29.6		41.2	
		29.8		39.6	
		30.2		38.1	
		31.2	31.8	37.4	39.6
	0.60	25.6		38.4	
		25.4		38.7	
		24.0		38.7	
		27.0		38.4	
		26.0	25.6	-	38.4
	0.80	14.4		38.6	
		14.0		39.5	
		15.2		38.4	
		14.8		37.7	
		13.8	14.4	39.7	38.8
	0.81	14.9		41.6	
		15.6		41.0	
		15.6		41.6	
		15.6		41.6	
		15.4	15.4	-	41.6
0.372	0.20	139.2		47.0	
		138.6		46.3	
		136.0		47.3	
		138.0		46.3	
		140.0	138.4	-	46.6
	0.25	83.8		50.0	
		84.0		48.5	
		83.5		49.8	
		85.0		47.7	
		76.2	82.5	52.0	49.6
	0.42	48.2		43.6	
		49.6		43.6	
		51.0		43.3	
		49.0		43.6	
		49.8	49.5	-	43.6

TABLE XII (CONT'D)

Extinguishment of UDMH Fires in 6.5-Sq in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining UDMH (Volume per cent)	Average
0.372	0.60	34.0		42.4	
		29.2		42.0	
		34.0		41.6	
		33.8		42.4	
		32.0	32.6	-	42.0
	0.81	19.0		43.0	
		18.4		43.0	
		18.0		43.0	
		18.2	18.5	42.7	43.0
		18.8		-	

TABLE XIII

Extinguishment of UDMH Fires in 49-Sq in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining UDMH (Volume per cent)	Average
0.186	0.21	60.0		33.4	
		60.0		31.2	
		60.0	60.0	35.0	33.3
	0.40	34.0		30.1	
		36.0		30.3	
		33.0	34.3	30.8	30.4
	0.59	23.0		31.1	
		26.0		32.0	
		22.0	23.7	32.0	31.7
	0.82	22.0		23.5	
		19.0		23.0	
		17.0	19.3	22.6	23.0
0.279	0.21	77.0		31.5	
		75.0		35.6	
		80.0	77.3	32.6	33.2
	0.40	45.0		37.0	
		42.0		36.0	
		42.0	43.0	37.1	36.7
	0.59	32.0		30.6	
		32.0		33.7	
		31.0	31.7	33.7	32.7
	0.82	30.0		29.7	
		28.0		30.2	
		29.0	29.0	31.4	30.4
0.372	0.21	100.0		35.0	
		102.0		37.2	
		99.0	100.3	35.0	35.7
	0.40	60.0		34.2	
		58.0		34.8	
		60.0	59.3	31.5	33.5
	0.59	42.0		34.4	
		47.0		34.0	
		40.0	43.0	37.2	35.2
	0.82	36.0		38.6	
		41.0		40.7	
		43.0	40.0	39.2	39.5
0.465	0.21	120.0		36.5	
		115.0		35.3	
		115.0	116.6	35.3	35.7
	0.40	71.0		37.6	
		67.0		38.2	
		72.0	70.0	36.0	37.3

TABLE XIII (CONT'D)

Extinguishment of UDMH Fires in 49-Sq in Burner by Water Sprays

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining UDMH (Volume per cent)	Average
	0.59	51.0		36.0	
		53.0		37.0	
		53.0	52.3	28.8	36.8
	0.82	49.0		38.6	
		47.0		38.6	
		52.0	49.3	35.6	37.6

TABLE XIV

Extinguishment of UDMH Fires in 324-Sq in. in Burner by Water Spray

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining UDMH (Volume per cent)	Average
0.279	0.60	50.0		29.5	
		53.0	51.5	29.1	29.3
	0.80	38.0		28.7	
		36.0	37.0	28.7	28.7
0.372	0.60	63.0		24.8	
		61.0	62.0	24.8	24.8
	0.80	49.0		29.1	
		50.0	49.5	28.9	29.0
0.465	0.60	67.0		30.6	
		68.0	67.5	31.0	30.8
	0.80	58.0		29.8	
		58.0	58.0	30.2	30.0

TABLE XV

Extinguishment of UDMH Fires in 6.5-Sq in Burner by Foam

Fuel Depth (inches)	Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of UDMH in Remaining Liquid (Volume per cent)	Average
0.093	0.20	26.7		41.6	
		25.4		47.5	
		29.0		45.2	
		25.6		44.5	
		26.0	26.5	42.0	44.1
	0.30	16.0		41.6	
		16.6		41.6	
		15.7		52.5	
		15.6		51.0	
		16.3	16.0	46.4	46.6
	0.36	14.6		39.3	
		14.8		43.4	
		14.9		42.8	
		14.4		42.8	
		14.3	14.7	44.5	42.6
0.186	0.20	33.4		52.1	
		32.3		56.2	
		34.2		54.0	
		32.6		54.7	
		33.5	33.2	37.2	54.2
	0.30	22.8		54.8	
		29.8		54.0	
		25.2		58.5	
		18.6		53.6	
		25.8	24.4	58.5	55.9
	0.36	20.0		49.2	
		17.4		49.0	
		20.1		48.0	
		22.2		48.0	
		21.5	20.3	48.4	48.5
0.279	0.20	44.1		55.5	
		47.3		54.7	
		50.0		56.2	
		49.8		55.5	
		51.1	48.5	59.5	55.9
	0.30	34.6		51.8	
		35.6		48.2	
		35.5		49.6	
		35.6		54.8	
		34.6	35.2	51.0	51.1
	0.36	28.6		50.1	
		29.2		50.1	
		29.4		53.0	
		29.5		53.0	
		28.4	29.0	50.8	51.4

TABLE XVI

Extinguishment of UDMH Fires in 49-Sq in Burner by Foam

Fuel Depth (inches)	Application Rate (gpm/Sq ft)	Extinguishment Time (Seconds)	Average	Concentration of UDMH in Remaining Liquid (Volume per cent)	Average
0.186	0.20	35.0		55.0	
		34.0		55.5	
		34.0	34.3	54.0	54.8
	0.32	22.0		53.1	
		24.0		52.5	
		24.0	23.3	52.5	52.7
0.279	0.20	60.0		57.3	
		56.0		57.3	
		58.0	58.0	57.8	57.5
	0.32	28.0		54.0	
		25.0		54.6	
		26.0	26.3	54.6	54.4
0.372	0.20	65.0		58.5	
		63.0		59.4	
		60.0	62.7	59.4	59.1
	0.32	30.0		55.5	
		30.0		55.5	
		29.0	29.7	55.8	55.6
0.465	0.20	65.0		60.5	
		66.0		60.2	
		65.0	65.3	60.5	60.4
	0.32	32.0		57.6	
		34.0		56.4	
		30.0	32.0	58.1	57.4

TABLE XVII

Extinguishment of UMDH Fires in 324-Sq in Burner by Foam

Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of UMDH in Remaining Liquid (Volume per cent)	Average
0.465	0.4	28.2		74.4	
		29.2	28.7	76.7	71.2
0.558	0.4	30.8		82.8	
		29.2	30.0	81.3	82.1
0.651	0.4	29.0		85.9	
		30.6	29.8	76.7	82.3

TABLE XVIII

Extinguishment of UDMH Fires in 6.5-Sq in Burner by Sodium Bicarbonate

Fuel Depth (inches)	Application Rate (lb-sq ft/sec)	Extinguishment Time (Seconds)	Average
0.093	0.094	2.0	
		1.9	
		3.0	2.3
0.186	0.094	2.0	2.0

TABLE XIX

Extinguishment of UDMH Fires in 49-Sq in Burner by Sodium Bicarbonate

Fuel Depth (inches)	Application Rate (lb-sq ft/sec)	Extinguishment Time (Seconds)	Average
0.186	0.0083	1.0	
		1.0	
		2.0	1.3
	0.0175	1.0	
		1.6	1.3
0.279	0.0083	no ext	
		2.0	
		2.4	2.2
	0.0175	1.0	
		2.0	
		1.6	1.5
0.372	0.0083	1.8	
		1.0	
		1.6	1.5
	0.0175	1.4	
		1.8	
		1.0	1.4
0.465	0.0083	2.0	
		1.0	
		1.2	1.4
	0.0175	10.8	
		1.4	
		1.0	1.2

TABLE XX

Extinguishment of UDMH Fires in 324-sq in Burner by Sodium Bicarbonate

Fuel Depth (inches)	Application Rate (lb-sq ft/sec)	Extinguishment Time (Seconds)	Average
0.279	0.016	4.0	
		2.4	3.2
0.372	0.016	3.0	
		5.2	4.1
0.465	0.016	3.2	
		4.0	3.6

TABLE XXI

Extinguishment of UDMH Fires by Various Agents

Agent	Fire Size (sq in)	Fuel Depth (inches)	Application Rate (gpm/sq ft)	Extinguishment Time (Seconds)	Average	Concentration of Remaining UDMH (Volume per cent)	Average
Water fog	49	0.186	0.2	77.0		34.2	
				76.0		31.2	
				75.8	76.3	31.0	32.1
		0.279		110.0		34.5	
				110.0		32.5	
				112.0	110.7	23.2	33.4
		0.372		150.0		36.2	
				148.0		34.5	
				150.0	149.3	35.0	35.6
		0.465		193.0		35.4	
				191.2		35.0	
				189.0	191.0	34.8	35.1
Trichloro trifluro ethane (Freon 113)	6.5	0.093	0.5	8.0			
				5.8	6.9		
		0.186		7.4			
				6.0	6.7		
		0.279		9.0			
				10.0	9.5		
		0.372		24.0	24.0		
Carbon dioxide (gas)	6.5	0.186	0.17[a]	no ext			
				70.0			

a. lb-sq ft/sec.

TABLE XXII

Extinguishment of 50:50 Mixtures Fires in 6.5-sq in Burner
By Water Spray

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.093	0.19	26.5		10.0		24.8	
		27.0		--		--	
		28.5	27.3	--	10	--	24.8
	0.21	25.2		13.6		28.1	
		25.2		13.6		27.7	
		25.4		13.6		28.1	
		25.0		13.6		27.4	
		25.6	25.3	13.5	13.6	28.3	27.9
	0.42	12.0		15.6		24.5	
		10.0		14.9		21.7	
		13.0		15.0		20.0	
		11.0		15.7		23.0	
		12.0	11.8	15.4		22.4	
	0.42	11.0		11.0		20.3	
		11.0		--		--	22.3
	0.60	7.5		11.0		16.2	
		7.5	7.5	--	11.0	--	16.2
	0.61	9.6		13.9		18.6	
		10.8		12.9		14.7	
		10.5	10.3	13.1	13.3	19.7	19.3
	0.62	7.4		12.3		13.8	
		7.0		12.5		17.5	
		7.0		13.5		16.2	
		7.2		13.2		18.2	
		6.9	7.1	13.1	12.9	18.9	16.9

TABLE XXII (cont'd)

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.093	0.64	8.5		14.6		19.4	
		6.7		13.5		18.0	
		7.1	7.4	14.7	14.3	20.4	19.3
	0.77	6.0		9.2		15.8	
		5.0	5.5	--	9.2	--	15.8
	0.80	5.0		11.5		17.0	
		4.6		12.2		16.5	
		5.0		12.4		16.9	
		5.2		12.2		16.4	
		5.0	5.0	12.8	12.2	15.9	16.5
0.186	0.19	38.0		10.0		31.6	
		38.0		--		--	
		37.0	37.7	--	10.0	--	31.6
	0.21	55.2		15.5		22.7	
		55.8		15.9		27.3	
		56.0		15.3		23.8	
		56.0		10.0		30.6	
		55.2	55.6	14.2	13.8	34.3	27.7
	0.42	25.0		15.4		23.4	
		26.0		17.0		23.6	
		26.0		17.0		24.4	
		25.0		15.5		24.0	
		26.0	25.6	15.6	16.1	24.0	23.9
	0.42	24.0		10.2		16.5	
		23.0		--	10.2	--	16.5
	0.60	13.0		13.7		18.2	
		13.0	13.0	--	13.7	--	18.2
	0.61	15.5		14.3		20.2	
		16.1		15.3		20.2	
		17.9	16.5	13.7	14.3	22.3	20.9

TABLE XXII (cont'd)

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.186	0.62	16.0		14.9		17.6	
		15.2		14.3		17.0	
		15.2		15.5		18.5	
		16.0		13.9		16.1	
		15.4	15.6	15.0	14.7	18.4	17.5
	0.64	15.6		15.1		21.2	
		14.1		16.1		22.5	
		19.2	14.8	14.2	15.1	21.8	21.8
	0.77	15.0		12.4		15.6	
		11.0	13.0	--	12.4	--	15.6
	0.80	12.2		13.5		17.1	
		12.0		15.2		16.9	
		13.0		12.8		15.9	
		12.6		13.2		15.9	
		11.8	12.3	12.6	13.5	15.8	16.3
0.279	0.19	46.0		10.0		37.8	
		47.0		--		--	
		45.5	46.3	--	10.0	--	37.8
	0.21	85.0		14.2		29.0	
		83.0		16.9		18.6	
		84.4		14.7		18.9	
		85.2		13.6		21.6	
		84.8	84.5	14.8	14.8	25.6	22.8
	0.42	40.0		14.8		23.3	
		39.0		15.3		20.8	
		41.0		15.7		22.5	
		38.0		15.7		22.6	
		42.0	40.0	12.6	15.4	19.9	22.3

TABLE XXII (cont'd)

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.279	0.42	38.0		11.1		16.9	
		36.0	37.0	--	11.1	--	16.9
	0.60	23.0		13.8		19.5	
		24.0	23.5	--	13.8	--	19.5
	0.61	21.2		17.4		29.3	
		21.8	21.5	15.1	16.2	21.8	21.8
	0.62	24.0		13.2		15.5	
		23.8		15.2		16.1	
		23.8		14.8		15.7	
		24.2		13.9		15.0	
		23.6	23.9	14.3	14.3	15.0	15.5
	0.64	23.2		15.7		22.6	
		24.8		15.2		22.4	
		25.8	24.6	15.4	15.4	21.0	22.0
	0.77	19.0		12.7		16.4	
		19.0	19.0	--	12.7	--	16.4
	0.80	18.0		13.7		16.7	
		18.4		13.6		16.1	
		17.8		15.0		19.0	
		19.0		14.0		16.8	
		18.6	18.4	12.6	12.8	15.4	16.8
0.372	0.21	115.0		13.8		23.4	
		110.4		18.6		28.5	
		117.0		14.5		29.5	
		116.2		14.2		29.4	
		117.0	115.1	19.4	16.1	32.6	28.7

TABLE XXII (cont'd)

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.372	0.42	50.0		14.0		25.7	
		54.0		14.8		26.6	
		52.0		14.9		24.2	
		54.0		13.4		24.2	
		53.0	52.6	14.6	14.5	24.2	25.0
	0.42	50.0		11.0		20.3	
		51.0	50.5	--	11.0	--	20.3
	0.62	32.0		14.3		12.8	
		31.8		14.9		12.7	
		31.2		16.8		15.8	
		31.8		15.9		16.6	
		32.0	31.8	15.5	15.5	16.0	14.8

TABLE XXIII

Extinguishment of 50:50 Mixture Fires in 49-sq in Burner
by Water Sprays

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.279	0.2	72.0		13.3		19.4	
		72.6		13.5		19.1	
		81.0	75.2	13.5	13.5	21.1	19.9
	0.4	32.0		16.1		19.2	
		35.5		14.1		18.3	
		31.8	33.1	13.5	14.6	20.5	19.4
	0.6	22.2		14.7		18.7	
		27.0		15.0		16.0	
		24.0	24.4	15.8	15.2	16.8	17.2
	0.8	19.2		14.2		17.5	
		18.2		15.1		20.1	
		18.8	18.7	16.2	15.2	18.9	19.2
0.372	0.2	97.6		13.1		20.8	
		97.2		15.0		19.9	
		98.8	97.9	14.7	14.3	20.4	20.4
	0.4	42.0		14.4		18.3	
		40.0		17.5		20.5	
		42.6	41.5	16.3	16.0	19.3	19.4
	0.6	30.8		17.5		17.4	
		29.8		18.2		16.9	
		28.6	29.7	16.7	17.5	18.5	17.6
	0.8	25.2		17.4		18.9	
		24.0		16.9		19.5	
		23.8	24.3	15.3	16.5	18.6	19.0

TABLE XXIII (cont'd)

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.465	0.2	117.8		15.3		19.3	
		123.0		15.4		20.8	
		120.0	120.3	17.1	16.3	18.5	20.3
	0.4	49.4		16.7		20.0	
		48.0		13.2		23.0	
		48.4	48.6	15.0	15.0	23.2	22.1
	0.6	35.8		15.2		20.1	
		34.4		15.1		20.1	
		35.2	35.1	15.0	15.1	21.8	20.7
	0.8	26.4		17.0		21.0	
		31.2		16.1		19.7	
		29.2	28.9	17.3	16.9	20.6	20.4

TABLE XXIV

Extinguishment of 50:50 Mixture Fires in 324-sq in Burner
By Water Spray

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.279	0.41	48.4		10.0		17.2	
		48.2		14.2		15.6	
		48.4	48.3	15.4	13.2	15.4	16.1
	0.60	38.0		12.3		15.8	
		35.6		13.4		17.2	
		36.0	36.5	12.4	12.7	18.0	17.0
	0.80	28.8		13.0		14.9	
		29.2		13.4		14.5	
		29.6	29.2	--	13.2	--	14.7
0.372	0.41	59.2		14.6		14.2	
		58.4		14.0		19.8	
		59.7	59.1	15.3	14.6	15.8	16.8
	0.60	47.4		12.2		19.1	
		44.6		13.3		20.3	
		46.8	46.3	13.7	13.1	18.3	19.2
	0.80	40.0		14.3		14.6	
		40.2		12.6		13.8	
		40.4	40.2	13.3	13.4	15.2	14.5
0.465	0.41	73.0		15.9		17.0	
		70.0		14.8		20.5	
		72.0	71.7	15.4	15.4	18.0	18.5
	0.60	57.0		13.5		19.3	
		56.6		13.4		20.4	
		56.2	56.6	13.0	13.3	19.8	19.8
	0.80	52.0		13.2		14.9	
		52.4		13.5		15.0	
		50.4	51.6	14.0	13.6	15.4	15.1

TABLE XXV

Extinguishment of 50:50 Mixture Fires in 2304-sq in Burner
By Water Spray

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.53	0.5	79.0		12.0		19.3	
		87.0		11.6		17.9	
		82.6	82.9	12.3	12.0	19.0	18.7
1.06	0.5	171.0		11.0		16.5	
		170.0	170.5	11.4	11.2	17.4	16.9

TABLE XXVI

Extinguishment of 50:50 Mixture Fires in 6.5-sq in Burner
by Foam

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.093	0.20	25.2		13.8		20.5	
		24.6		13.8		24.0	
		24.6		10.9		18.3	
		25.0		20.1		19.3	
		28.0		15.2		19.9	
		23.4		--		--	
		25.0	25.1	18.7	15.4	25.4	21.2
	0.30	16.0		16.2		26.8	
		17.0		16.3		26.9	
		15.8		16.2		26.9	
		17.0		18.0		23.2	
		16.0	16.5	18.0	16.9	23.0	25.4
	0.40	12.0		22.4		25.4	
		11.8		21.0		26.4	
		11.8		21.9		26.6	
		13.0		21.5		15.3	
		13.0		16.0		22.7	
		10.8		22.6		28.1	
		13.0	12.2	23.5	22.3	26.4	24.4
0.186	0.20	34.6		14.9		25.6	
		35.2		14.6		25.9	
		35.0		17.0		26.0	
		36.0		21.7		25.9	
		35.0		27.0		24.4	

TABLE XXVI

Extinguishment of 50:50 Mixture Fires in 6.5-sq in Burner by Foam

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.093	0.20	25.2		13.8		20.5	
		24.6		13.8		24.0	
		24.6		19.9		18.3	
		25.0		20.1		19.3	
		28.0		15.2		19.9	
		23.4		--		--	
		25.0	25.1	18.7	15.4	25.4	21.2
	0.30	16.0		16.2		26.8	
		17.0		16.3		26.9	
		15.8		16.2		26.9	
		17.0		18.0		23.2	
		16.0	16.5	18.0	16.9	23.0	25.4
	0.40	12.0		22.4		25.4	
		11.8		21.0		26.4	
		11.8		21.9		26.6	
		13.0		21.5		15.3	
		13.0		16.0		22.7	
		10.8		22.6		28.1	
		13.0	12.2	23.5	22.3	26.4	24.4
0.186	0.20	34.6		14.9		25.6	
		35.2		14.6		25.9	
		35.0		17.0		26.0	
		36.0		21.7		25.9	
		35.0		27.0		24.4	
		34.2		20.5		26.2	
		35.0	35.0	26.2	20.3	27.5	25.9

TABLE XXVI (cont'd)

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.186	0.30	23.8		21.6		26.5	
		23.8		21.0		28.2	
		24.2		20.6		27.5	
		24.0		24.6		25.2	
		24.0	24.0	24.6	22.5	25.4	26.6
	0.40	15.0		22.6		[illegible]	
		15.4		22.0		26.2	
		15.4		--		--	
		15.0		30.4		22.9	
		15.5		21.2		29.0	
		14.6		28.2		26.4	
		16.6	15.3	27.8	25.4	29.6	26.8
0.279	0.20	46.2		21.3		27.6	
		45.8		20.2		26.0	
		45.0		15.0		22.6	
		46.5		36.2		20.6	
		46.0		22.0		24.5	
		40.0		31.2		35.7	
		49.6	45.6	20.1	23.8	25.8	26.1
	0.30	29.6		22.8		29.4	
		28.2		23.3		30.6	
		29.4		26.6		30.0	
		30.0		24.2		27.5	
		28.0	29.0	23.9	24.2	21.6	27.8
	0.40	18.4		28.4		30.4	
		18.6		28.4		30.0	
		18.8		--		--	
		18.0		20.6		29.0	
		19.0		21.2		26.9	
		20.4		29.2		26.5	
		19.6	19.0	28.2	26.0	24.4	27.9

TABLE XXVI (cont'd)

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Composition of Remaining Liquid: UDMH (wt per cent)	Average	Hydrazine (wt per cent)	Average
0.372	0.20	56.8		--		--	
		57.0		17.2		23.8	
		56.4		19.7		24.9	
		58.0		24.4		27.0	
		60.0		28.3		23.2	
		57.3		21.1		27.8	
		55.4	57.3	24.7	22.6	26.6	25.6
	0.30	34.6		22.6		26.7	
		34.2		22.4		26.2	
		35.0		20.0		26.6	
		34.0		25.0		24.3	
		38.0	35.2	34.6	24.9	19.5	24.7
	0.40	22.0		34.1		21.9	
		22.0		23.2		28.6	
		22.2		25.6		23.1	
		22.4		25.7		23.0	
		22.4		--		--	
		23.8		30.2		27.5	
		23.2	22.6	30.0	28.1	29.6	25.6

TABLE XXVII

Extinguishment of 50:50 Mixture Fires
in 49-sq in Burner by Foam

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Composition of Remaining Liquid UDMH (wt per cent)	Hydrazine (wt per cent)
0.279	0.20	57.0	22.8	26.4
		55.6	20.1	25.8
	0.32	24.4	24.9	32.2
		26.2	25.2	30.4
0.372	0.20	61.2	21.5	29.6
		60.8	21.5	28.7
	0.32	30.4	24.7	32.8
		30.2	23.5	31.6
0.465	0.20	65.0	24.9	29.4
		65.8	23.4	31.1
	0.32	32.2	25.0	33.2
		33.0	23.1	32.9

TABLE XXVIII

Extinguishment of 50:50 Mixture Fires
in 324-sq in Burner by Foam

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Composition of Remaining Liquid UDMH (wt per cent)	Composition of Remaining Liquid Hydrazine (wt per cent)
0.465	0.4	42.6	19.3	25.3
		19.8	33.3	42.5
		16.8	32.2	43.0
0.558	0.4	20.0	34.3	43.5
		16.0	--	--
0.651	0.4	17.2	35.8	41.6
		19.0	34.6	40.6
1.12	0.4	25.0	32.6	39.6
0.279	0.4[a]	36.0	--	--
0.372	0.4[a]	45.2	--	--
0.465	0.4[a]	65.0	--	--
0.465	0.4[a]	69.0	--	--
0.651	0.4[a]	87.0	--	--

a. 6% ordinary foam (American LaFrance).

TABLE XXIX

Extinguishment of 50:50 Mixture Fires
in 2304-sq in Burner by Foam

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Composition of Remaining Liquid UDMH (wt per cent)	Composition of Remaining Liquid Hydrazine (wt per cent)
0.53	0.27	29.0	--	--
		29.2	--	--
1.06	0.27	29.2	--	--
		30.0	--	--

TABLE XXX

Extinguishment of 50:50 Mixture Fires
in 49-sq in Burner by Sodium Bicarbonate

Fuel Depth (in)	Application Rate (lb-sq ft/sec)	Extinguishment Time (sec)
0.0465	0.0133	1.0
		1.0
		1.0
		1.0
		1.0

TABLE XXXI

Extinguishment of 50:50 Mixture Fires
in 324-sq in Burner by Sodium Bicarbonate

Fuel Depth (in)	Application Rate (lb-sq ft/sec)	Extinguishment Time (sec)	shment sec)
0.279	0.0133	7.0	
		3.0	
0.372	0.0133	4.5	
		8.0	
0.465	0.0133	4.5	
		3.0	

TABLE XXXII

Extinguishment of 50:50 Mixture Fires in 2304-sq in Burner by Sodium Bicarbonate

Fuel Depth (in)	Application Rate (lb-sq ft/sec)	Extinguishment Time (sec)
1.06	0.0167	9.0
		6.0

TABLE XXXII

Extinguishment of 50:50 Mixture Fires in 2304-sq in Burner by Sodium Bicarbonate

Fuel Depth (in)	Application Rate (lb-sq ft/sec)	Extinguishment Time (sec)
1.06	0.0167	9.0
		6.0

TABLE XXXIII

Extinguishment of 50:50 Mixture Fires by Various Agents

Agent	Fire Size (sq in)	Fuel Depth (in)	Application Rate (lb-sq ft/sec)	Extinguishment Time (sec)
Bromo-trifluoro methane	6.5	0.186	0.01	No ext
			0.02	No ext
			0.02	No ext
			0.03	No ext
			0.03	No ext
			0.03	No ext
			0.04	No ext
			0.04	No ext
			0.04	No ext
			0.04	No ext
			0.04	No ext
Carbon dioxide (gas)	6.5	0.186	0.17	No ext
			0.17	No ext
			0.17	No ext

TABLE XXXIV

Extinguishment of 50:50 Mixture Fires in Silo[a]

Agent	Application Rate	Extinguishment Time (sec)	Remarks
Sodium bicarbonate	0.0005 lb-sq ft/sec	Immediate	Reignited when lighted match thrown into silo
	0.0065 lb-sq ft/sec	Immediate	Reignited when lighted match thrown into silo
Water Spray	0.8 gpm/sq ft	31.0	Spray nozzle 3 feet above burning fuel
		8.0	Spray nozzle 1 foot above burning fuel
		32.0	Spray nozzle 3 feet above burning fuel
		2.8	Spray nozzle 1 foot above burning fuel
		12.5	Spray nozzle 3 feet above burning fuel
		2.1	Spray nozzle 1 foot above burning fuel
Alcohol Foam	0.4 gpm/sq ft	25	Foam dropped directly into burning fuel
		19	Foam applied to silo wall
		26	Foam dropped directly into burning fuel
		16	Foam applied to silo wall
Carbon dioxide (solid)	3 ounces	No extinguisnment	Dry ice thrown into burning fuel

a. 0.465 inch of fuel in 4-foot silo, 12 inches I.D.

TABLE XXXV

Extinguishment of JP-X Fires in 6.5-sq in Burner
by Water Spray

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Concentration of UDMH Remaining (volume per cent)	Average
0.093	0.20	36.0		10.7	
		29.0		17.1	
		32.8		21.5	
		34.8		16.8	
		33.4	33.2	9.2	15.1
	0.41	55.0		8.5	
		40.4		6.2	
		40.7		8.8	
		37.7		15.2	
		42.3	43.2	9.4	10.0
	0.60	25.0		9.6	
		25.2		9.8	
		31.8		11.3	
		35.2		8.8	
		32.4	29.9	9.2	9.7
	0.8	22.7		9.4	
		19.0		7.9	
		19.0		8.5	
		24.8		7.6	
		17.9	20.7	11.0	8.9
0.186	0.41	82.2		8.5	
		75.6		10.6	
		95.2		12.7	
		76.4		12.8	
		88.4	83.6	12.2	11.4
	0.60	60.3		11.0	
		65.0		10.7	
		65.2		10.4	
		61.2		11.3	
		52.1	60.8	11.7	11.0
	0.80	47.5		10.5	
		49.5		9.8	
		49.1		9.2	
		47.3		9.9	
		47.7	48.2	8.2	9.5

TABLE XXXV (cont'd)

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Concentration of UDMH Remaining (volume per cent)	Average
0.279	0.40	116.0		11.3	
		103.1		12.1	
		92.3		14.0	
		96.4		13.1	
		112.6	104.1	12.8	12.7
	0.60	79.6		12.5	
		82.4		12.2	
		78.1		12.2	
		80.0		12.4	
		77.1	79.4	12.5	12.4
	0.80	61.3		11.3	
		62.8		12.2	
		64.3		10.7	
		62.2		11.0	
		61.0	62.3	11.2	11.3

TABLE XXXVI

Extinguishment of JP-X Fires in 49-sq in Burner by Water Spray

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Concentration of UDMH Remaining (volume per cent)	Average
0.186	0.40	75.0		3.3	
		70.0		3.3	
		68.0	71.0	3.6	3.4
	0.58	58.0		4.4	
		57.0		4.9	
		60.0	58.3	4.8	4.7
0.279	0.40	82.0		5.9	
		84.0		5.9	
		82.0	82.7	6.4	6.1
	0.58	60.0		8.9	
		61.0		9.0	
		60.0	60.3	9.0	9.0
0.372	0.40	97.0		6.8	
		97.0		9.0	
		95.0	95.7	9.2	8.3
	0.58	63.0		11.6	
		62.0		11.4	
		63.0	62.7	11.3	11.4
0.465	0.40	106.0		9.5	
		105.0		8.9	
		110.0	107.0	10.5	9.6
	0.58	65.0		11.6	
		65.0		11.7	
		64.0	64.7	10.8	11.4

TABLE XXXVII

Extinguishment of JP-X Fires in 324-sq in Burner by Water Spray

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Concentration of UDMH Remaining (volume per cent)	Average
0.279	0.60	180.0		4.0	
		185.0	182.5	4.0	4.0
	0.80	175.0		3.9	
		175.0	175.0	3.7	3.8
0.372	0.60	190.0		4.0	
		200.0	195.0	4.0	4.0

TABLE XXXVIII

Extinguishment of JP-X Fires in 6.5-sq in Burner by Foam

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Concentration of UDMH Remaining (volume per cent)	Average
0.093	0.20	35.8		13.8	
		39.0		14.8	
		36.2		15.0	
		38.1		16.5	
		34.4	36.7	17.2	15.9
	0.30	25.6		12.8	
		28.0		14.6	
		27.6		14.7	
		25.0		17.2	
		26.7	26.5	18.3	15.5
	0.35	24.6		14.4	
		23.0		20.2	
		19.5		16.2	
		19.4		16.5	
		21.0	21.5	13.0	16.1
0.185	0.20	53.1		20.6	
		40.0		26.3	
		50.7		13.2	
		58.7		15.0	
		49.7	50.4	23.0	19.6
	0.30	37.8		16.2	
		33.8		17.2	
		33.2		17.2	
		34.2		16.6	
		31.4	34.1	26.3	18.7
	0.35	26.2		22.8	
		26.0		24.8	
		28.4		26.6	
		26.4		28.2	
		24.3	26.2	27.5	26.0
0.279	0.20	73.2		20.6	
		73.8		16.8	
		69.7		25.3	
		70.0		15.3	
		69.8	71.3	12.8	18.4
	0.30	19.0		40.5	
		48.1		18.4	
		49.5		17.8	
		50.0		17.8	
		47.4	48.7	19.9	18.9
	0.35	32.2		26.0	
		37.4		22.0	
		33.2		32.1	
		32.4		41.3	
		31.5	33.4	33.3	31.9

TABLE XXXIX

Extinguishment of JP-X Fires in 49-sq in Burner
by Foam

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Concentration of UDMH Remaining (volume per cent)	Average
0.186	0.20	35.0		4.0	
		32.0		4.0	
		32.0	33.0	4.0	4.0
	0.32	15.0		28.5	
		15.2		27.2	
		16.0	15.4	26.0	27.2
0.279	0.20	39.0		7.6	
		36.0		8.2	
		40.0	38.3	4.2	6.7
	0.32	18.0		33.2	
		16.0		33.3	
		17.[illegible]	17.2	33.9	33.5
0.372	0.20	42.0		23.1	
		44.0		22.9	
		41.0	42.3	23.3	23.1
	0.32	19.0		33.9	
		19.0		33.0	
		20.0	19.7	35.4	34.1
0.465	0.20	45.0		30.4	
		50.0		30.4	
		48.0	47.7	31.0	30.6
	0.32	19.0		39.2	
		20.0		40.0	
		19.0	19.7	38.8	39.3
0.405	0.40	19.6		56.8	
		19.8	19.7	51.4	54.1
0.558	0.40	21.0		67.5	
		19.0	20.0	72.2	69.9
0.651	0.40	20.8		70.6	
		21.0	20.9	70.6	70.6

TABLE XL

Extinguishment of JP-X Fires in 324-sq in Burner by Foam

Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average	Concentration of UDMH in Remaining Liquid (volume per cent)	Average
0.465	0.40	19.6		56.8	
		19.8	19.7	51.4	54.1
0.558	0.40	21.0		67.5	
		19.0	20.0	72.2	69.9
0.651	0.40	20.8		70.6	
		21.0	20.9	70.6	70.6

TABLE XLI

Extinguishment of JP-X Fires in 6.5-sq in Burner
by Sodium Bicarbonate

Fuel Depth (in)	Application Rate (lb-sq ft/sec)	Extinguishment Time (sec)	Average	Average
0.093	0.055	1.6		
		1.0		
		1.2	1.3	1.3
0.186	0.055	1.4		
		1.6		
		1.4	1.5	1.5
0.279	0.055	2.0		
		1.6		
		2.2	1.9	1.9

TABLE XLII

Extinguishment of JP-X Fires in 49-sq in Burner
by Sodium Bicarbonate

Fuel Depth (in)	Application Rate (lb-sq ft/sec)	Extinguishment Time (sec)	Aver.
0.186	0.0083	1.0	
		1.2	
		1.0	[illegible]
	0.0175	0.8	
		1.0	
		0.6	[illegible]
0.279	0.0083	0.8	
		1.0	
		2.2	1
	0.0175	2.0	
		1.0	
		3.0	2
0.372	0.0083	1.0	
		1.2	
		1.6	1
	0.0175	3.0	
		1.0	
		1.4	1.
0.465	0.0083	1.0	
		1.0	
		2.0	1.
	0.0175	1.8	
		1.0	
		1.0	1.

TABLE XLII

Extinguishment of JP-X Fires in 49-sq in Burner by Sodium Bicarbonate

Fuel Depth (in)	Application Rate (lb-sq ft/sec)	Extinguishment Time (sec)	Average
0.186	0.0083	1.0	
		1.2	
		1.0	1.1
	0.0175	0.8	
		1.0	
		0.6	0.8
0.279	0.0083	0.8	
		1.0	
		2.2	1.3
	0.0175	2.0	
		1.0	
		3.0	2.0
0.372	0.0083	1.0	
		1.2	
		1.6	1.3
	0.0175	3.0	
		1.0	
		1.4	1.8
0.465	0.0083	1.0	
		1.0	
		2.0	1.3
	0.0175	1.8	
		1.0	
		1.0	1.3

TABLE XLIII

Extinguishment of JP-X Fires in 324-sq in Burner
by Sodium Bicarbonate

Fuel Depth (in)	Application Rate (lb-sq ft/sec)	Extinguishment Time (sec)	Average
0.279	0.016	5.0	
		3.0	4.0
0.372	0.016	4.8	
		5.0	4.9
0.465	0.016	5.8	
		4.8	5.3

TABLE XLIV

Water Spray Extinguishment of Fires Oxidized by Nitrogen Tetroxide Vapors[a] in 6.5-sq in Burner

Fuel	Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average
Hydrazine	0.028	0.6	3.3	3.3
	0.093	0.6	9.0	
			10.0	9.5
UDMH	0.093	0.6	21.6	
			22.7	
			22.2	22.2
50:50 Mixture	0.093	0.29	26.1	
			26.0	26.0
		0.40	20.3	
			20.[illegible]	20.6
		0.60	15.0	
			16.[illegible]	15.8
		0.80	[illegible]	
			[illegible]	4.9
	0.186	0.29	[illegible]	
			[illegible]	65.3
		0.40	[illegible]	
			[illegible]	54.9
		0.60	38.0	
			36.6	37.3
		0.80	17.5	
			19.8	18.7
	0.279	0.29	103.0	
			102.8	103.9
		0.40	79.6	
			77.4	78.5
	0.279	0.60	49.8	
			50.0	49.9
		0.80	31.1	
			28.0	29.6

a. [illegible] of N_2O_4 vapors directed onto surface of fuel.

TABLE XLIV (cont'd)

Fuel	Fuel Depth (in)	Application Rate (gpm/sq ft)	Extinguishment Time (sec)	Average
50-50 Mixture	0.372	0.29	141.0	
			139.0	140.0
		0.40	106.2	
			106.8	106.5
		0.60	58.0	
			59.1	58.5
		0.80	40.2	
			41.9	41.0

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